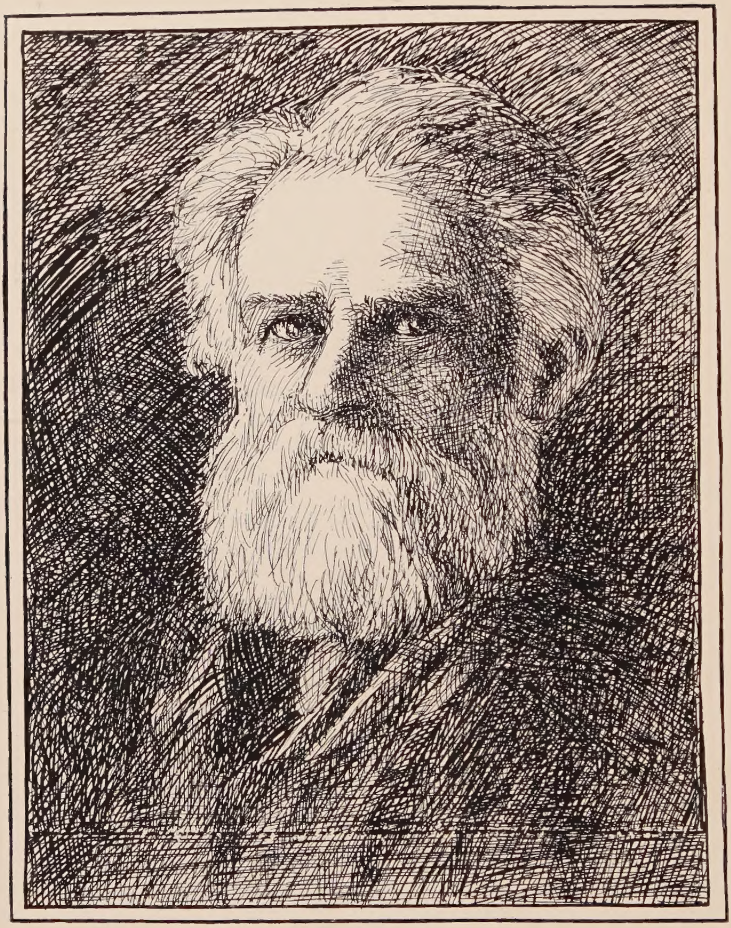
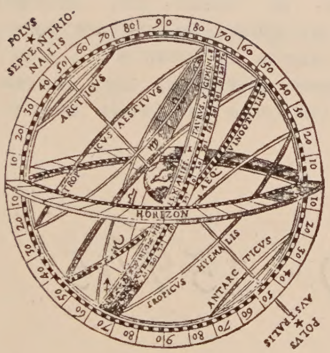


Plate I: Simon Newcomb (1835-1909)
(Crow-quill interpretation of an original photograph by Mr. William Henry)

HENRY SMITH WILLIAMS

THE GREAT ASTRONOMERS



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TO

MY FRIEND

SPENCER ARMSTRONG

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POSTSCRIPT:

(INTRODUCED HERE BECAUSE THIS SEEMS TO BE THE BEST PLACE FOR IT.)

The appendix and the pictures in this book may be regarded as auxiliary features thrown in for good measure. I hope that many readers will find them helpful.

The appendix contains explications of a good many subjects—from Aberration of Lenses to Zenith Angles and the Zodiac—which the text may have mentioned but incidentally or not at all—because the text is explicitly a story of the human implications of astronomical discoveries and progress, rather than an explication of the discoveries themselves.

The appendix contains also a series of star-charts, which I designed and executed with a good deal of care, and which will be found to depart somewhat from the conventional star-charts of technical works, I hope helpfully. The *mosaic* presentation of the constellations, in which the field of the entire heavens may be taken in at one eye-sweep, is at least novel, and so far as I am aware unique. Used in connection with the regional charts of more conventional order (which also have certain original features), these charts will, I hope, be found to serve a genuinely useful purpose for the amateur star-gazer.

The numerous diagrams scattered through the text, illustrating such subjects as precession of the equinoxes, the moon's phases, the principles of action of telescopes, and what not, are obviously designed to serve a similar purpose. I have sketched them casually, with an eye to the explication of principles, rather

than with any thought of technical perfection of treatment such as a mechanical draftsman would effect.

Perhaps a word should be added about the portraits, of which there are about fifty, ranging in execution from thumb-nail sketches to somewhat elaborated drawings, executed in various mediums.

In drawing these pictures I have necessarily held to originals more or less hackneyed by oft-repetition—for even I am not old enough to have seen most of the great astronomers in the flesh. But where, as not infrequently happens, the available original portraits differ so much among themselves as to leave a good deal of doubt as to what was the actual appearance of the famous personage in question, I have permitted my pencil or pen or brush to adopt a compromise—producing an interpretation or a composite picture, rather than a replica of any model.

For example, my crayons insisted on depicting Copernicus in humanized departure from the caricatures that pass for original portraits of the great Emancipator—but in so doing they held, nevertheless, to the essential facial contours which, since they appear in all portraits, probably have a measure of authenticity.

Such compromises, however, are on the whole exceptional. As a rule, authentic portraits exist, and of course I have not ventured to depart from the essentials of such portraits. My object in re-drawing them in different mediums has been chiefly my own amusement. Often a sketch was made for momentary diversion on the leaf of a note book, when I chanced to come on a portrait of exceptional authenticity, or unusual appeal, in consulting source books—as, for instance, the original Memoirs of Bradley—in a public library.

At the moment of making such sketches, I had no thought of using them to illustrate this book. But when it was suggested that a series of portraits would add to the interest of the text, and

serve a really useful purpose in enabling the reader to envisage the personages whose deeds make up the story of astronomical progress, I very gladly sought the co-operation of an old-time friend, the crow-quill (for many years superseded by the paint-brush) in order to transpose the note-book memoranda into line-sketches that could be reproduced on book paper.

A crow-quill gets a bit rusty in the course of thirty years of disuse, but appears not to be damaged beyond at least partial repair. As to the latter point, however, you must decide for yourself.

An element of personal interpretation enters into every portrait, done in whatever medium; but most of all, perhaps, into such line work as I have here employed, where the crow-quill is used with the freedom of an etcher's needle. Whatever an artist's training (and my own chances to have been comprehensively cosmopolitan), his pen-drawings are as individual as his pen-writing. So the present series of sketches may perhaps establish a personal relationship between illustrator and reader that is at once more direct and more intimate than could be attained through the less elemental medium of the printed word.

It remains only to add that, with pictures as with text, I have been sedulous to credit sources. Even though my drawings may depart rather widely from the originals in manner of handling, I have always captioned a reference to the source, except in a few instances where a detached photograph or engraving of untraced origin has been the basis of my transcription.

Even in cases where my pen has transformed an outline diagram into a full-toned picture, I very gladly express my indebtedness to the maker of the diagram, which after all is the *essential* of the illustration—the added figures and shadings being merely auxiliary embellishments. The word "adapted" in the caption-credits is designed to exculpate the originator of the diagram from complicity in the embellishment.

FOR THE TIMID READER—
A WORD OF FAIR WARNING

It is only for the sake of concreteness that the title of this book names astronomers. Were it not for the ambiguity of such a title, the name might be "The Great Emancipators."

Emancipators of mankind from the bondage of primaeval superstition: that is the rôle in which the great astronomers appear, as their accomplishment is here conceived.

I personally care almost nothing for the chief part of the mere concrete facts of astronomical discovery. I do not see that it matters at all whether the stars number a few thousand, as was supposed in pre-telescopic days, or the tenth power of the thousands, as a modern photograph of the heavens suggests. I do not see that it matters intrinsically whether the stars themselves are points of light—the tiny candles they seem—set in a glassy sphere, or whether they are gigantic suns coursing through infinite depths of ether.

These things, in themselves, do not matter. Merely to know whether stars are what they seem or something very different would hardly be worth the time and effort required to answer the question, had we merely learned the concrete answer after the effort was made.

What really matters is something quite different. What really matters is that man's conception of his own relation to the scheme of things was closely bound up with his interpretation of the nature of the stars. This was a world of relativity, long before an Einstein came to dramatize the word. And man's conception of his own position in this world of relativity had come to be

intimately associated with—nay, was explicitly dependent on—his interpretation of the nature of the heavens.

Because he conceived the stars to be the flecks of light that they seemed; because he thought the sun and moon merely larger lanterns designed to give him light and warmth; because he conceived this earth to be the enormous central structure of the universe—he came to think of himself as the final product of a cosmic scheme which his unevolved intelligence had not yet enabled him to conceive as other than the result of a creative effort such as he himself put forth when he fashioned an implement of stone.

Because of that astronomical misconception, the spirit of man came to be bound up with the stars. It came to be enmeshed in fundamental misconceptions that could never have arisen had man known from the outset what we know today of the essential relative position of ourselves and the universe.

Emancipation could come only with knowledge. The truth alone could set man free. And the emancipators could be none other than the iconoclasts who, one generation after another, sharing with their fellows the wonder as to what the stars really are, were moved to endeavor to find out.

The truth shall set you free. But man had come to like his bondage. He did not wish to be set free. He would not even accept freedom when it was offered, but must needs struggle with fanatic zeal to remain within the chrysalis of superstition in which he had enmeshed himself.

Like the butterfly of a certain poet's conception which crawled back into the chrysalis, he did not wish to be a winged creature; he wished to remain a worm.

But the emancipators would not have it so. In their quest of

truth, they tore open the chrysalis. Not because they sought the rôle of liberators. Simply because emancipation was the inevitable outcome of their effort.

It was, indeed, because of this inevitable sequel rather than because of the specific things that they did, that the men whom we name as great astronomers are famous. It is because of this that the story of what they did is worth telling.

In attempting to present the story, I find myself in full sympathy with a writer of my acquaintance who once had the ambition to inscroll a mighty epic of the Civil War without mentioning a single name or a single date.

Inasmuch as an epic is, by definition, a record of the deeds of valiant men, such an ambition was obviously futile.

By the same token, the story of that vastly more consequential work of emancipation implied in the title of this book cannot be told without mentioning names and presenting concrete observations. And the names being those of the men called astronomers, we cannot avoid all mention of stars in telling this story.

But from first to last it is not the stars in themselves that really interest us. The thing of interest is man's relation to the stars.

And so, here at the beginning, I warn you that if your interest is in stars, as such, rather than in men, this book is not for you. Any text-book on astronomy will better serve your purpose. This is the story of what the great astronomers taught us, not about the stars, but about ourselves.

If, being thus warned, you care to proceed, it is at your own peril—as the road-makers' signs inform motorists regarding a highway under repair. At least you cannot say that you were not forewarned.

For those mental voyagers who choose not to heed the warn-

ing, this story of the great astronomers as spiritual Emancipators of our race is written.

If in spite of this disavowal you should find that these pages contain a good deal of mere information about stars, I can only plead the limitations of the medium, in extenuation. A famous writer of comic operas once said to me, with a whimsical smile, that every comic opera must contain at least one joke. Similarly, a book about man's relation to the stars cannot be written without at least occasional reference to the stars themselves.

But enough of explanations. If you still care to go ahead, the road is open.

YOU ARE INVITED TO TAKE A PRELIMINARY CRUISE IN STARLAND

IT WILL not be long now, I suspect, before we have airplanes that can fly six hundred miles an hour. If you had such an airplane, adequately fueled, you could fly round the world in our middle latitudes in twenty-four hours.

Round the World in a Day

That would be a feat worth talking about—the circumnavigation of our big globe in a single day—keeping directly under the sun all the way, and matching his flight mile for mile.

But now suppose that an airman, flying thus at a uniform speed of ten miles a minute, could start straight up into the air and could continue in a bee line on a Jules Verne voyage off into space.

How long would it take him, think you, to get to our neighbor Mars—at the nearest point of his orbit?

Why, something over nine years.

A Trip to Neptune

That would be a tiresome voyage,—not to speak of the absence of air and the frigidity of empty space. Yet it would constitute only the beginning of an exploratory tour across the solar system.

If our phantom voyager were disposed to see something more of the world-system of which the earth and Mars are minor members he might pass on through the region of the swarming minor planets, called asteroids or planetoids, and only after 70 years of flying would he come to Jupiter,—something really worth while in the way of planets, bulking 1300 times bigger than the earth.

Another period of 76 years would be required to cross the gap between Jupiter and Saturn. The journey from Saturn to Uranus would require 170 years; the jump to Neptune 190 more; and

the final stage to the trans-Neptunian planet of 1930 would take perhaps something like 500 years.

Thus the entire journey from the earth to the farthest known planet would require not far from 1000 years.

If we recall that the craft which thus required five centuries to pass from our earth to its most distant planetary neighbor required but 24 hours to circumnavigate the earth itself, we shall pretty clearly realize that our solar system is a stupendous structure.

5,000,000 Years to the Nearest Star

But all things are relative. And if we would fully grasp the situation, we must reflect that the journey to trans-Neptune brought us only to the frontier of our little solar system. We are still, so to speak, at home.

If we wish really to see something of the outside world, we must go on at least to the nearest star.

And how long will that take?

Well, in round numbers five *million* years, holding to the same ten-mile-a-minute speed that brought us to Mars in ten years and to Neptune in five hundred.

That is to say, the star that is our nearest neighbor in space lies about 5,000 times as far away from us as the remotest member of the sun's planetary family hitherto discovered.

The trip to Neptune bears the same relation to the trip to the nearest star that a brisk half hour's walk here on the earth bears to the circumnavigation of the globe.

Millions for Units

As to the stars that make up the main galaxies that greet our eyes whenever we glance skyward, it is futile to attempt to give a notion of their distances in terms of mundane measurements.

To say that our ten-mile-a-minute aeroplane would require a hundred *million* years to reach a star of average distance, and

twenty or thirty *billion* years to come to the remoter stars of the galaxy, conveys little meaning, since millions and billions, however glibly phrased, are incomprehensible terms.

But whether or not such distances are comprehensible, they represent actual magnitudes with which the astronomer, when he charts the heavens, must deal as familiarly as the surveyor of land deals with rods and miles.

To make his figures a little more manageable, the astronomer adopts a new unit of measurement. He estimates stellar distances in terms of "light-years," the light-year being the distance that light, compassing 186,000 miles per second, travels in 365 days.

This distance—the astronomer's foot rule—is almost six million million miles. You write it thus: 6,000,000,000,000.

The nearest star is at a distance of about four and a third light-years. The farthest stars revealed by telescope are thousands, even millions, of light-years away.

Meantime light comes to us from the sun in eight minutes, and travels on to Neptune in about four hours, and to Lowell's trans-Neptunian planet in perhaps seven hours.

A Magic Airplane

Four and seven hours. Here at last are figures that one can comprehend. And at once a new idea to cap the figures. Here it is:

Light requires seven hours to go to the far planet. According to Einstein, light is the speediest messenger in the universe. But you and I know better than that. There is one messenger that out-speeds light by so wide a margin that it can go to Transneptune not in hours, but in an infinitesimal fraction of a second.

This really speedy messenger is called Imagination.

The speed of Imagination is no paltry snail's-pace of 186,000 miles per second. It is a thousand or a million or if you prefer a billion or a trillion times that.

And where Imagination goes, we may go at the same speed—laughing at the sunbeams as we flash by them. So now I am about to ask you to start out with me, with Imagination for our guide, on an airplane journey that will not find us flying for 500 years to get to the frontiers of the solar system; nor for five and a half hours even, as required by light; but which will enable us to flash out beyond the orbit of Neptune, and to cross the intervening space to the nearest star, and on to the center of our galaxy (60,000 light-years away), and yet on and on in a circuit of the entire galactic system—in a term of minutes.

In other words, I invite you to join me in a cruise of the universe—a personally conducted cruise, with Imagination for our guide—in the magic airplane Parsec.

A Real Speed-Craft

It is specified that the craft shall have such speed-qualities as to give us glimpses of all the worth-while sights of the galactic system, and land us back home within three hours. The start is at ten. We shall be back in time for a one-o'clock luncheon.

As we go aboard and are about to start, perhaps you may be interested to know the origin of the rather odd name of our magic vehicle. Where did we find the name "Parsec"?

The explanation is that the word "parsec" is familiar to astronomers as an abbreviation of "parallax second," meaning the distance at which a star must lie in order that it shall have the parallax of one second of arc. Otherwise stated, the distance at which a star must lie in order that, seen from the star, the angles subtended by the radius of the earth's orbit shall be one second, or one-thirty-six hundredth of a degree.

It appears that this represents a distance of about three and a quarter light-years—a light-year, as we have seen, being the

Plate II: The Great Nebula in Orion (Mt. Wilson Observatory)

distance that light, traveling 186,000 miles per second, compasses in 365 days.

Stated in miles, the distance represented by our parsec is approximately shown by this row of figures: 20,000,000,000,000.

That happens to be about three-quarters of the distance to the nearest star. It seems a long distance, certainly. Yet for our present purpose it must rank only as a unit distance, as it does for the astronomer.

When specifications were given for the airship Parsec, I knew that it would not suffice at all to think of one parsec as a long distance, any more than one thinks of a mile as a long distance, when speaking of the flight of an ordinary airplane.

The specifications called for a maximum speed of not less than 10,000 light-years per minute.

Nothing less than that would enable us to make the promised tour of the universe, with assurance of getting back at the lunch hour.

But so resourceful a builder as Imagination is not stumped by even such figures as that. So it is guaranteed that the airplane Parsec will transport us at this really notable speed. But it is understood, also, that on occasion the magic craft can slow down to the minutest fraction of the maximum, so that we may have opportunity for leisurely observation of at least a few of the more famous stellar exhibits along the way.

First We Cruise Around the Solar System

All this has been made clear by the advance agent. Now we are off.

The engine is throttled to the lowest speed as we cruise out to the orbit of Mars, our nearest neighbor. A rather insignificant planet, smaller even than the earth, with a snowcap at the pole, and presenting some evidence of vegetable life, but nothing of

especial consequence, in comparison with the sights that are ahead.

We pass on and linger but a moment to circle about big Jupiter with its eight moons and then on to Saturn, circling to glance at its really interesting rings; and on to the eighth planet Neptune. Notable for the way in which we mortals of the planet Earth discovered it, rather than for anything it has directly to exhibit. Likewise the ninth, Transneptune, here at its frontier.

And now for a cruise into inter-stellar space.

Full speed ahead!

Full speed, it will be recalled, means about 10,000 light-years per minute. A dizzy speed. We should not even realize that notable stars are flashing by, did not the pilot slacken the pace when we come near any worth-while world-system.

But the pilot knows his business, and in the course of a quarter hour our craft has slackened speed now and again that the guide might point out, first half a dozen of our neighbor-stars, distant from the earth only five or ten or twenty light-years. Then there was the group of Pleiades,—the "little dipper"—which we passed, off at the right, within two or three parsecs, so that they looked startlingly wide-spaced, like the Great Dipper seen from the earth. There, too, at a somewhat lesser distance was the brilliant Sirius, a hundred times brighter than our sun, the guide tells us, but not unduly dazzling as seen through our protective spectacles.

And then gigantic Betelgeuse, big enough, we are told, to fill the orbit of Mars, if he were placed where our sun is, but so tenuous of structure that we should not know, save for the heat, if we were actually imbedded millions of miles in its substance, as we should be if it took the place of the sun.

Looking back now casually, we see that our sun appears to be

only one of a cluster of stars, not very unlike the Pleiades as we are accustomed to see them—an almost nebular cluster, seemingly somewhat isolated from other stars.

Looking Back on the "Home Cluster"

This, we are told, represents our own "Home Cluster," made up of stars that really are separated one from another by spaces

FIG. 1.—A Globular Cluster.

of five, ten, or twenty light-years, though from our present distance they seem crowded together almost as compactly as globular clusters seem when viewed from the earth.

And now we are nearing one of the globular clusters,—though we should scarcely know it had we not been told, because from our present distance the individual stars are spread out with such wide spaces between them that we should not suspect that

they all belong together. We are told presently that we are passing through the very midst of a globular cluster, and that really these stars are a somewhat isolated system,—it being only the distance of the group from the earth that makes them seem compacted into a round structure.

Off beyond we see a whole galaxy of stars, spread out in every direction, some bright and some dim, with patches of nebulosity that are transformed into isolated stars as we approach.

This, we are told, is one of the Magellanic clouds—as we of the earth term it. There is nothing cloud-like about the great universe of stars composing it, on nearer view. "Just about a hundred thousand light-years from the earth," the guide remarks casually.

Circling the Milky Way

And now veering a little, we find ourselves in a region where stars seem equally abundant in every direction.

We are in the midst of the Milky Way—that vast highway of stars, running clear round the system of which our sun is a part, like a great ring, with individual stars so numerous that from our viewpoint on the earth, the whole structure seemed nebulous.

Now we find it merely a system of scattered stars, no different in appearance from other portions of the heavens we have traversed.

We are told that we are in the midst of some of the nebulosities that seem most dense when viewed from the earth. Here they are not nebulosities at all, but stars scattered as we are accustomed to see them scattered in most regions of the sky, with only here and there a nearer one which has the aspect of our own sun as we flash by at a distance of a hundred million miles or so.

Down toward the center of the course we are now circling, there are many faint nebulosities, and one of these the guide

points out as our own Home Cluster, no longer appreciable as a group of stars, but only as a faint veil of light, of pinhead size.

We are traveling far. A glance at the illuminated clock there on the wall of the limousine-like vestibule of the Parsec, shows that we have been flying for about half an hour, and this means that, since we have perhaps averaged two-thirds maximum speed,

FIG. 2.—A Spiral Nebula.

we are now at a distance of about half a million light-years from home. The Home Cluster has disappeared altogether.

Nebulæ Off to Starboard

Yet off at one side there are nebulous clusters that we recognise as spiral nebulae, visible to the naked eye, but still nebulous in structure, as we have seen them in photographs made with a big telescope back on earth.

These nebulae lie far outside our own galactic system, which

we are circling, the guide tells us, and even with our magic craft we have not time to visit them. They are island-universes, so far away that were we to go out to them, our own galactic system, as we looked back at it, would appear only as itself an isolated nebula—larger, perhaps, than any one of the others, but one cannot be certain even of that. At most, a "continent nebula" of which each of the outlying "island universes" is a replica.

"How many stars have we seen so far?" somebody asks.

"Perhaps fifty billion," the guide responds airily. "Of course we don't count the ones in the spirals off there on the horizon, which still seem nebulous. They are thrown in for good measure."

100,000,000,000 Stars on View

Our sky Baedeker, had we time to read it, would tell us that the galactic system round which we are cruising has a population of something like a hundred billion stars. Apparently we are by way of seeing most of them before we are through.

Incidentally, there are two very odd features of our journey, which at first we hardly noticed. The first is that, although it was broad daylight when we left the earth, it is full night out here in space. Only when we chance to come fairly near a star—that is, within a hundred million miles or so—is it light enough so that we could consult our guide book if we wished to. The darkness makes the spectacle all the better, of course. But it does seem odd when one glances at the illuminated face of the clock and realizes that it is almost noon back there at the earth.

But the second feature is even odder. Something, indeed, that seems out and out spookish. Things seem to have no weight out here. We are in a closed limousine, and could not fall out, but apparently there would be no danger of our falling out anyway. There seems to be no up and no down—nowhere to fall.

If there chances to be a bright cluster of stars down below us,

the pilot turns the plane right over, and the cluster that was below it now seems at one side, or overhead. Apparently it makes no difference at all which way our heads are pointing.

Upside-Down and No Harm Done

The first time we turn over to get a better view of a cluster of stars down below us, some of the passengers clutch at things, thinking they are to be spilled out. The guide laughs.

"People always think this upside-down business odd," he says. "It really isn't any funnier than that people in New York and people in Tokio walk about feet to feet, with heads in opposite directions. Out here we are so far from any gravitation-center that directions don't count."

All the same it does seem a bit spookish. But one gets used to it.

Homeward Bound

Presently we are aware that we have completed the circuit of the galaxy, because the cluster of nebulosities which we still recognise as the group in which our sun lies is almost directly ahead of us, instead of off at one side as hitherto.

And before we know it, the guide is saying:

"Do you see how the Home Cluster is enlarging, as we approach? Now the stars that are grouped round our sun are separated, and the sun itself stands out—that yellow star, smaller than many, but of perhaps average size, there toward the right. We are only thirty or forty thousand light-years away now, and we are going to circle about at this distance so that you may have opportunity to inspect our own earth, through the magic binoculars that each of us will now put on."

Magic binoculars they are, for through them the earth, which before was invisible, now stands out like the moon seen through a big telescope.

Again the guide is speaking:

"Perhaps you have not thought of it, but now you will realize

We Have Flown Backward in Time

that, in flying off into space at a speed so many times the speed of light, we have in effect flown backward in time. For now, out here thirty thousand light-years from the earth, we are of course receiving the light that left the earth thirty thousand years ago. What you are looking at then, is the earth as it was in that prehistoric period. This is the first of the panoramic earth-views we promised you."

The explanation continues: "It is now twelve o'clock, you see, Greenwich standard earth time, and we are almost at the end of our journey. But we shall not return directly.

"For the next quarter hour we shall circle to the left as if moving in an orbit about the earth of which, as you see, you now have a good view through the side windows.

"After a long five minutes or so, during which we shall make full circuit round the earth, we shall return a little nearer and make another circle. And so, by easy stages, we shall make our way back to the starting point according to schedule, and give you ample opportunity to witness the promised panorama.

"If you look at your itinerary, you will find that the view promised at that hour is called 'the earth in the old stone age.'"

The Earth in the Stone Age

And as we glance through our magic binoculars, we do indeed see the promised view.

Before our very eyes, off there on the planet Earth, we see men clad in skins, with clubs for weapons, pursuing strange beasts like hairy elephants on the land surface which we recognise as Europe. And in America—there on the Manhattan Island we left two hours ago—the great skyscrapers have vanished, and in their place there are only woodlands and bare outcropping rocks, with here and there a group of huge tusked mastodons and other strange creatures.

What can it mean? Are we merely dreaming? Have we gone mad, that such phantasms haunt our eyes?

Yet we know the answer. This is the panorama that we have come forth to see. This is what the advertisements promised us —quite as folders to allure one on a round-the-world tour tell us of sights in India and Egypt.

We know that we are now looking back in time, and for the moment, veritably living in an age some thirty thousand years remote because the good airship *Parsec* brought us here at many times the speed of light.

Now we are making the cross flight to let light catch up with us.

The revealing rays that enter our eyes are the light-rays that left the earth thirty thousand years ago, and, creeping along snail-like, at a mere 186,000 miles per second, have taken all the intervening years to reach the region to which the up-to-date *Parsec* now brings us on the return trip.

Today Is Also Yesterday

The clock there on the wall tells us that the hour is twelve; the calendar shows that it is the 4th of July, of the year 1930. Time is no different for us from what it would be if we had remained back there in Manhattan. The two hours that have elapsed during our journey are precisely the same our friends on the planet Earth are passing in the usual way.

And yet, we who are living in the day called July 4th, 1930, are also living in a definite even if unnamed day of a definite even if not clearly dateable year so remote that in the interval the earth has made something like thirty thousand revolutions about the sun, punctuated with more than 10,000,000 rotations on its axis.

Assuredly, the publicity man of the *Parsec* Company did not exaggerate when he promised us a novel and thrilling experience.

And now the ship is heading again straight toward the earth and our actual return journey has begun. A few minutes we whirl on toward the earth in a straight line—for fifteen minutes, twenty. These are actual minutes, as our watches show. The plane is flying slowly now, to give opportunity for better view of the panorama.

Yet in the twenty minute interval, we have witnessed a shift of scenes there on the earth, like a fantastic newsreel run across the screen at dazzling speed.

We Witness Pyramid-Building

And now as the *Parsec* swings about at right angles, and again takes an orbital course, so that the newsreel runs at normal speed, and gives us clear visual images, it appears that great patches of the earth's surface have been transformed; that cities have come into being in the territories we recognise as Asia and the region of the Mediterranean.

In the valley of the Nile, we see men building a great structure which we recognize as a Pyramid approaching completion.

And we know that we have come forward by some twenty thousand years in time—twenty thousand revolutions of the earth about the sun, which as we approach have been whirled off, with pin-wheel aspect, far too fast for counting.

As now for another quarter hour we take the orbital course, circling round the world, we see that America is still without such evidences of man's presence as we saw in Asia and Europe, but that the animal life has changed in the two-minute interval. The mastodons have gone and only deer and bison and elk remain in their place. These are pursued by red Indians in clothing of skins, using rough-stone weapons; though down in the neck of land between the two Americas we see evidences of civilization more like that of Egypt.

A Star-Land Movie

But now again we are headed earthward and again the picture is blurred. For the rest of the return trip, however, the schedule has promised us, we are to stop at shorter intervals.

A single minute of our flight, even at lowest speed, brings us so much nearer the earth, that we must again swing about and circle; and so the remainder of our return journey will be mostly spent thus circling and witnessing successive days of mundane existence—each day represented by only a few minutes of time marked by our watches, as we circle round the earth; and each succeeding day being fifty or a hundred years later in human history.

Is the picture clear?

The conditions are quite simple and tangible. We are approaching the earth stage by stage, and stage by stage we are therefore encountering spheres of light-rays which, spreading in all directions, left the earth at successively later periods.

All the light-rays travel at the uniform speed of 186,000 miles per second, and the vibrations in the ether of each successive stratum of light-rays are equivalent to the image on a movie negative—a permanent record of visual conditions at a given instant.

And we, receiving these images at any given part of our journey, are effectively in the same position as a movie audience, which similarly re-lives the past as it witnesses on the screen the events which really happened last week, last month, or last year.

The difference is merely that, out here in space in our airplane *Parsec,* we are witnessing events that took place not last week or last year, but centuries ago.

For us, as for the movie audience, this is the 4th of July, 1930. But while the movie audience is watching the progression

of, say, events of twenty, ten, or five *days* ago, we are watching the events of twenty, ten, or five *centuries* ago.

In a word, as the movie audience re-lives the events of the past few weeks and days, we are reliving the events of past eras and centuries.

This Is Not Einsteinian Relativity

It is all very simple, all perfectly tangible—nay, all inevitable, so long as the *Parsec* holds to its speed, reduced now to about 100 parsecs per minute.

And as yet its motor shows no sign of failing.

Circle after circle we make, each time a few minutes nearer the earth, as our watches mark the time; a century or so nearer to the year 1930 A.D. as the historic newsreel is screened on the background of the earth itself before our eyes.

Details of the successive reels need not be rehearsed. Indeed, by this time our eyes are almost exhausted with the bewildering splendors of the successive pictures, in which the whole pageant of human progress from the time of the Pharaohs has been witnessed at first hand—actually witnessed with contemporary vision; yet, paradoxically, viewed from beginning to present culmination (from age of Pyramids to age of skyscraper) in the space of an actual sixty minutes.

And at last, almost home again, we circle about Alpha Centauri that nearest star neighbor, and know that we are less than two parsecs (a mere four and a third light-years or, say, 25 trillions of miles) from home. Here we listen to *radio* messages of the year 1926—for radio waves travel with the speed of light. The view on the earth as we thus circle to salute our neighbor, reveals the scenes of the year 1926.

The space-gap separating us from the earth has narrowed to negligible dimensions.

The time-gap separating present and past is now reduced to years instead of centuries.

Home Again in Space and Time

We may close both gaps, looping the loop about each of our sister planets as we descend, and find ourselves back at Mitchell Field on Long Island precisely on schedule, one P.M. Eastern Standard Time (which is six P.M. Greenwich or world time).

And so ends our round-the-Stellar-System three-hour tour in the airplane *Parsec,* at the promised speed of 10,000 parsecs (thirty-five hundred light-years) per minute, with that admirable *avant courier* Imagination for our guide and interpreter.

It has been such a journey as could not possibly have been conceived, much less undertaken, before our own day. The very word parsec is a word of our own time. There was no need of such a word until recent generations, for there was no conception of the ideas that made such a unit of measurement necessary.

Only within the past century, and notably within the term of the present generation, has the true vastness of the universe been comprehended.

Less than three centuries have passed since it was proved that light travels at finite and measurable speed.

Only since the beginning of the 19th century has it been known even to the leaders of thought that Time is long. Prior to that it was believed that our earth was less than 6000 years old, and what was accepted as the authoritative records declared that the earth was created before the sun and moon and stars.

The same record told of a firmament solidly vaulted and supporting primeval waters yet older than the earth. The entire mechanism of earth and heavens was conceived as a structure of such relatively diminutive size that it might be stored in a

corner of the solar system as we now know it, without obstructing the movements of the planets.

Another Voyage into the Past

Our trip in the good airplane *Parsec* has given us visual demonstration both of the breadth of space and the length of time.

Let me now invite you to make another voyage into the past, quite different in plan, but under guidance of the same mentor, Imagination, to witness in more leisurely manner the sequence of events from the time of the Pyramid-builders forward, with reference in particular to those attempted explorations of time and space through which one generation after another of keen-eyed and inquiring-minded men—peering out into the starry depths through which our *Parsec* voyage has just carried us—slowly and laboriously garnered new series of facts and interpretations based on concrete observation—from which ultimately emerged a transformed conception of the size, the structure, the nature, the origin, and the destiny, of the world in which they found themselves.

Let us, in other words, take up the story of the great deeds of the Great Astronomers.

It is a far descent from the flight through space at hundreds of parsecs per minute, with stars for companions, to the slow progress among the faltering phrases and blurred images of the pages of a book.

But if you will think of these pages as constituting a sort of guide-book to the scenes that you witnessed, but had not always time to dwell on, in the course of the *Parsec* journey (somewhat as one reads geographies and histories to refresh one's memory after a tour round-the-world), perhaps the pictures supplied by your own imagination may form a background that

will give a vividness and glamor to the successive scenes that I dare not hope the words by themselves can evoke.

And in that case, you will feel in the end that the *Parsec* voyage was indeed a memorable journey and that the story of astronomy, however faultily here presented, is intrinsically among the most important sagas of human experience.

I invite you, then, to this second voyage—a journey with stars for a background, indeed, yet primarily amidst human scenes the record of which is from one viewpoint a story of astronomical achievement, and in another and larger view, the story of how man strove to comprehend and chart the universe and how, somewhat in proportion as he succeeded in opening up new realms of the stars, he succeeded also in finding himself.

A story, that is to say, not primarily of the stars, but of man's relation to the stars.

BOOK I

THE OLD HEAVEN

"And God made the firmament, and divided the waters which were under the firmament from the waters which were above the firmament: and it was so. And God called the firmament Heaven.

"And God made two great lights; the greater light to rule the day and the lesser light to rule the night: he made the stars also. And God set them in the firmament of the heaven to give light upon the earth."

—*Oriental Anthology.*

"Hast thou with him spread out the sky, which is strong, and as a molten looking glass?"

—*Oriental Anthology.*

I

THE MAGIC FEATS OF ERATOSTHENES

A Watcher of Shadows

It was the day of the summer solstice. The year was not far from the close of the first century of the rule of the Ptolemies in Egypt. A man in Greek costume was standing on the flat roof of the library building in the city of Alexandria, eagerly awaiting the moment when the sun should cross the meridian.

The man was not watching the sun itself. He was watching, with keenest scrutiny, a shadow cast by the sun—the shadow of an upright peg, which had been adjusted with meticulous accuracy in the vertical position.

The shadow-watcher was tall, spare, with the aspect of a dreamer. He stroked his long gray beard meditatively, as he stooped to note the slow creep of the shadow toward the meridian line. A very young man—hardly more than a boy—kneeled on the other side of the post, and watched the shadow with an expression of puzzlement. Presently he spoke:

"Are you sure, Master Eratosthenes, that this shadow will really tell you the size of the world?"

The older man nodded, without raising his eyes.

"There can be no doubt of it," he said. "It is very simple, but I will explain it to you once more."

"I will attend carefully, and try to understand, but it seems very mysterious. To measure the size of the whole earth by merely looking at a shadow, here in Alexandria! It seems quite impossible."

"It is not impossible. Nor is it even very difficult," said the master serenely, still watching the shadow. "But you have not stated the conditions accurately. I shall not measure the world merely by looking at this shadow. By itself, that would tell me nothing about the size of the world. But you know that men have measured the distance along the earth to Syene, and found it five thousand stadia. And you know that Syene lies in a direct line south of us."

"All that I know well, Master Eratosthenes."

"And have I not told you that on this day of the solstice, when the sun comes farthest north in its journey, a vertical post such as this casts no shadow in Syene, because the sun is directly above, at the zenith, so that it shines down to the bottom of the deepest well?"

Measuring the Earth

"That, too, I remember, Master. It is the rest that puzzles me. I know that the world is round, both because you have told me, and because I can see ships from the housetop that cannot be seen when I stand on the shore, and the sails come into view before the ships themselves. It seems strange, and hard to believe —and many people cannot believe it at all; but I know it is true. And I know that a vertical line always points straight toward the center of the earth, because you have told me so."

"Yes, so I have told you, and it is true. And it follows, does it not, that the line of this vertical post, here in Alexandria, cannot be parallel with the line of a vertical post in Syene, or any distant place—since, starting from widely separated places, they come together at the earth's center, like spokes of a wheel at the hub?"

"It must be so, Master, yet it seems very strange. Does it mean that if there are people on the other side of the world,

their feet also point toward the center of the globe, and so, compared with us, they walk with their heads downward?"

"That would be true if the other side of the world were inhabited. But we have reason to believe that there is only water there. No people can live, even on this side of the globe, much below the line of the tropic, there at Syene, nor very far to the north. One region would be too hot, the other too cold; and to east and west, as your geography has taught you, land ends, and beyond is only water, though once there was a continent called Atlantis, off beyond the Pillars of Hercules."

Though he thus answered freely the young man's questions, Eratosthenes did not for an instant neglect the creeping shadow. Now it was almost at the meridian line. A few moments more, and the two lines coincided.

The old man motioned to his companion to come closer, and note with what accuracy he marked the end of the shadow with a sharp-pointed stylus. He waited a few minutes, to observe that the shadow now appreciably lengthening showed that the true meridian had been tested. Then he rose to his feet, and regarded the youth complacently. He unfolded a sheaf of tablets that had hung by his side, and began drawing outlines on one leaf with the stylus.

"See how simple it is," he explained. "The sun is so far away that its rays that come to Syene and those that come to us here may be regarded as parallel. You have studied geometry, and know what I mean. The rays are not truly parallel, of course, since they come to different places on the earth from the sun, but the distance of the sun is so great, in comparison with the earth's size, that we may call the rays parallel, without significant error."

Again the youth interrupted. "Is the sun, then, so very far

away?" he queried. "It seems very near, because it is so bright. Is it farther away than the moon?"

"Eighteen or twenty times as far away, and therefore it is vastly larger than the moon, since to our eyes they seem of the same size. Aristarchus of Samos has measured the distances, and he thinks that the sun, being so enormous, must be at the center of the universe, and that the earth revolves round it. If that is true, the world is turning round and round from west to east, so that the sun seems to move through the sky from east to west."

"And is that true, Master?"

The old Greek stroked his beard, as was his wont when meditating or in doubt. "I do not feel sure," he said. "I am more a geographer than an astronomer, and the evidence to me is not conclusive. We will talk more about that another time. Now let me give you the further explanation of the measurement we are making, and then I will make the calculation—which will not be difficult, now that we have the angle to guide us."

"It would be not only difficult, but impossible, for me," said the youth frankly.

"Not when I have told you how to do it. What puzzles you, perhaps, is that you are thinking of the shadow cast by the vertical post. But the shadow, as such, does not concern us. We watched the shadow merely to note the exact point of its end when the sun was at the meridian. If now we fasten a string to the top of the post, and bring the other end of the string to the point here that I marked as the end of the shadow, that string indicates the line of the sunbeam that cast the shadow, does it not?"

"I see that clearly," said the youth.

"And we can measure the angle between the string and the post?"

"Surely."

"Well, that angle is the one we are seeking. That shows us, in effect, how far this post, here in Alexandria, leans, in comparison with the post, also vertical, in Syene. And as I draw the lines here on my tablet, you will see from your geometry—the proposition that tells about the angles made by parallel lines cutting

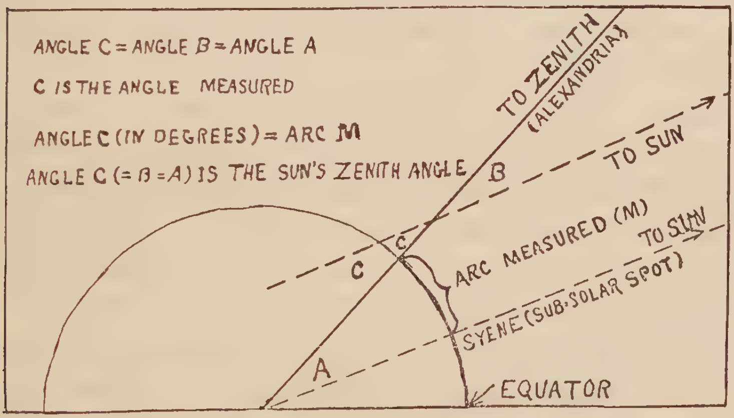

FIG. 3.—The Earth Measurement of Eratosthenes.

another line, you remember—that the angle between the string and the post is of the same size as the angle at the center of the earth between the extended post at Syene and this post here likewise extended to the earth's center. It is a matter of mere observation to find how many degrees of arc this angle subtends. Do you understand what I mean?"

"I think so. Any circle, large or small, is divided into the same number of degrees—three hundred and sixty. So the length of a degree varies indefinitely with the size of the circle considered."

"Precisely. And with a radius of given length, you can inscribe a circle of only a given size. No matter how many circles you draw, they will be the same size."

"That is clear."

"And if you measure an arc of that circle, and then are told what angle lies between the two radii that subtend the arc, you can readily compute the size of the circle, can you not?"

"Surely. If the angle is, for example, ten degrees, it takes thirty-six such angles to complete the circle. And so the measured arc must be multiplied by thirty-six to give the circumference of the circle."

"Bravo! You have stated the whole case. Now we have only to apply what you have said to our earth-measuring problem. The arc of the circle about the globe which we have measured, namely, the distance from Syene to Alexandria, is five thousand stadia. The angle we have just measured, with the aid of the sun and the post, is—let us test it."

He held up a leaf of his tablet on which angles of various sizes were inscribed, and placed it back of the juncture of post and string for comparison.

"It is an angle of something over seven degrees, as you see," he said. "Let us say, seven degrees and twelve minutes. That would be"—he made a rapid calculation—"just one fiftieth of three hundred and sixty degrees, would it not."

"I cannot do such sums in my head," said the youth, "but I can see that it is not far wrong."

"You will find it quite right, I think. And now, can you multiply five thousand stadia by fifty?"

"That is not so difficult. It would be two hundred and fifty thousand stadia."

"Right. And that, as you see, must be the distance round the world," said Eratosthenes, smiling. "So we have found it a very simple thing to survey the earth, without travelling more than one-fiftieth of the way round it."

"It does not seem to me very simple," said the youth, "though I think I now understand just what you have done."

He regarded the venerable geographer with frank admiration as he added, naively, "And I think it very wonderful."

The old Greek smiled, and waved his hand deprecatingly. "I don't know that it matters much just how big the earth is," he said, "since men can live only upon a small patch of its surface. But it was an amusing experiment."

Eratosthenes Measures the Ecliptic

Precisely six months after the day on which he had measured the earth, Eratosthenes and the youthful Hipparchus were again engaged in the study of the sun's shadow, at the top of the library building at Alexandria.

They had been there many times in the interim, but this day, the 21st of December, was to give data of altogether exceptional significance. This being the day of the winter solstice, the shadow to be observed would be, of course, the longest of the year. The difference between this shadow and the short shadow that had been measured and recorded on the 21st of June, would represent the amount of the sun's departure from an even equatorial course in its successive annual journeys across the heavens.

"Have you never made the measurement on the winter solstice day before?" young Hipparchus questioned.

"I have made it many times, and with a good degree of accuracy," the Master told him. "But this perfected gnomon will give us an added measure of accuracy, while at the same time making our task very simple."

The instrument to which Eratosthenes referred looked, at first glance, like a brass kettle, about two feet in diameter, and half as deep—perfectly round and uniform in shape, like a spherical globe cut precisely in two, and the upper half discarded.

It was hollow, like a kettle, and at the bottom, in the exact center, was a little post of metal about ten inches high, which would obviously be exactly perpendicular when the kettle rested in natural position, supported, so that its rim was precisely horizontal. If you looked carefully, you saw that the interior of this hemisphere was not merely polished, but marked with fine lines, circling concentrically at regular intervals.

Eratosthenes called the youth's attention to the lines.

"You know, of course," he said, "that these lines divide the surface into degrees and fractions of a degree. We are going to measure the angle the sunbeam at the top of the post makes with the vertical post, just as we did before. But now we shall not need to use a string and actually measure the angle itself. We need only look where the end of the post's shadow comes, and read the answer directly from these lines on the spherical surface. I call the apparatus an 'armillary sphere.' It is a simple affair, but we shall find it convenient."

"I think it is a very wonderful invention," said the youth with customary enthusiasm.

"Hardly that," said the venerable inventor. "It involves no new principle, and I feel that I have been rather stupid not to think of making such a device before. But we have it now, and we must level it exactly, and fix it in position before the sun gets much nearer the meridian. A few cups of water in the bottom, below the level of the shadow, will enable us to do that easily."

The adjustment was soon made, and presently the sun came

to the meridian, and the precise angle of the shadow was read from the scale, and recorded, on the page of a tablet-sheaf where the similar record made six months earlier was already inscribed.

Eratosthenes compared the two records with eager interest, and computed the difference, which he found to be forty-seven degrees, forty-two minutes, and thirty-nine seconds of arc. He showed the result to the youth, who watched with almost awed attention.

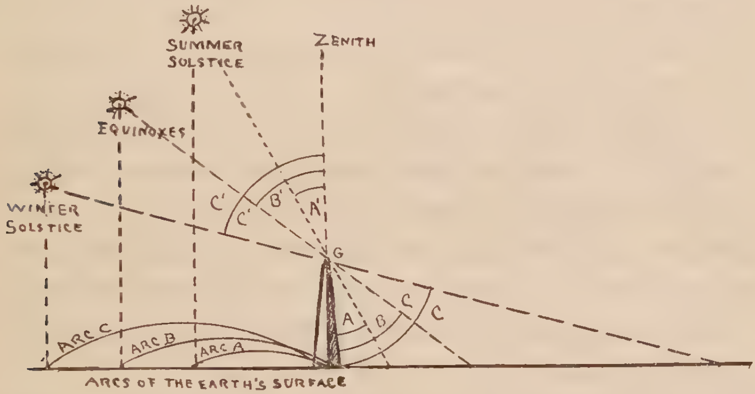

FIG. 4.—The Principle of Eratosthenes. Angles A, B, and C (or A′, B′, C′) Measure Respectively Arcs A, B, and C of the Earth's Surface.

"Half that amount," he said, "or a little less than twenty-four degrees, represents the distance the sun departs, southward in winter and northward in summer, from the plane of the earth's equator. You can make the division accurately for yourself, and at the summer solstice next year we will measure again, with this new apparatus, to verify our other observation. But we shall not find it far wrong, I think."

"It seems very strange to me," said the youth, "that the sun should wobble about in its course, instead of going in the same

path. And more strange still, perhaps, that it should vary only by just so much from the equatorial plane year after year—since it chooses to vary at all."

"If it kept the same equatorial course, we should have no change of seasons throughout the year," the savant explained. "And if its changes were not uniform, the seasons would be chaotic, and our part of the world would be as uninhabitable, perhaps, as those regions off toward the equator where no one can live now."

"All that I can understand," said Hipparchus, "but I cannot understand why it is so arranged."

Eratosthenes smiled benevolently. "The gods have so willed it," he said. "I know no other answer. But if you say that this is hardly better than no answer at all, I shall not dispute you. At least we may count it something, though, that we have learned from studying the shadows just what path the sun does travel."

"That is indeed much," said Hipparchus. Then buoyed by the enthusiastic optimism of his youth, he added:

"I shall remember all the things you have taught me, Master Eratosthenes, and when I am older I shall study the sun very diligently, and perhaps I shall be able to find out the explanation of its strange wanderings."

The venerable astronomer, who—though the foremost man of science of his age—was also a poet, recalling the dreams of his own youth, smiled indulgently.

Finding the Latitude of Alexandria

"In the meantime," he said, "there is another application of the information we have just gained that I think will interest you. You remember that we measured the angle of the sun on the day of the summer solstice. Do you recall what we found the angle to be?"

"Certainly, Master. It is seven degrees and twelve minutes."

Eratosthenes was making a computation on his tablet. He nodded approval, and then held the tablet for the lad's inspection.

"Those simple figures tell us something that no man ever knew before. They tell us where we are on the surface of the globe—just how far we are from the equator. You see how simple the computation is. As we have just found that the width of the Tropic Zone, in which the sun wanders, is forty-seven degrees and something over forty-two minutes, half that amount is the farthest distance the sun departs from the equator at the time of each solstice. Here are the figures, you see—23 degrees, 51 minutes, and some seconds. The sun was that far north of the equator when we measured it last summer, and found it 7 degrees and 12 minutes from us, here in Alexandria."

Young Hipparchus gave an exclamation of delight. "And that means that by adding these sums, as you have done, we find the distance of Alexandria from the equator—31 degrees and a little more than 3 minutes, you have written it. How wonderful!"

"Perhaps it is too simple to be called wonderful," Eratosthenes demurred. "But as I said, it is a new truth that has interesting implications. It is something that we are the first persons in all the world to know just where we live on the globe—a truth that was withheld even from such master-thinkers as Pythagoras and Anaxagoras and Aristotle. But far more important is the fact that our new knowledge will give us a fixed point of reckoning as a basis for maps of the habitable world, which will aid not alone the scientific students of geography, but merchants and travelers everywhere."

"It is very wonderful!" the youth repeated.

With that verdict, every modern will agree. Creative genius of the highest order was required to devise such experiments, even though the experiments themselves were truly simple, and seem almost crude in the light of the perfected technique of our own day. But it is the discovery of the new principle that really counts.

And the principle of earth-measurement that Eratosthenes utilized is the same that has guided every navigator and explorer from Columbus to Admiral Byrd.

Had not the old Greek divined the applicability of that principle, it is by no means unlikely that America might remain an undiscovered continent even to this day—for all geography of the Roman period had its source in Eratosthenes, and it was this geography that guided Columbus.

As to the accuracy of the results attained by the first earth-measurer—that is a matter of altogether minor significance.

It was not possible that the observation of shadows should rival in accuracy the telescopic study of the declination of stars with a modern transit instrument; or even the mariner's sighting of the sun with a perfected sextant. Moreover, Eratosthenes was misinformed by the Ptolemaic surveyors as to the exact location of Syene—which in fact is neither exactly on the Tropic of Cancer nor directly on the meridian of Alexandria.

Here, then, were two sources of practical error. But, as it chanced, the two virtually neutralized each other, and a modern commentator has estimated that the famous measurement did not err by more than one percent from the truth as modern geographers, after generations of effort, have determined it. Moreover—and this is still more remarkable—the measurement of the ecliptic with the perfected gnomon led Eratosthenes, we are told, to locate

Alexandria at parallel 31 degrees 3 minutes of North latitude; and modern geography locates it at 31 degrees 12 minutes—a difference of less than ten miles!

The Distance of the Sun

On yet another occasion, master and pupil are together.

"There are some studies of the sun," said Eratosthenes, "that were made not long ago by Aristarchus of Samos, and which led him to very remarkable conclusions. We might make some similar studies one of these days, if you like."

The youth, Hipparchus, expressed his delight by look and eager word.

"Can we begin at once?" he queried.

"We must wait till the moon is precisely at the half," the master told him. "You will understand why when I have explained what we are to do."

"Is it something I shall be able to understand?"

"Very readily, if you recall your geometry lessons about simple angles, as I am sure you do. Indeed, there is only one principle involved, and that is the very simple one that if you can determine the size of one of the acute angles of a right-angled triangle, you can chart the entire triangle, showing the exact relative lengths of all its sides."

"I remember that proposition very well," said Hipparchus.

"Here, then, is the application. The moon shines by the reflected light of the sun, as you know. So when the moon is seen by us as precisely a half moon, the line of our sight, to the moon, must make precisely a right-angle with the line of the sun's rays which illuminate the part of the moon we see. Is that clear?"

"I had not thought of it before, but it could not be otherwise."

"If, then, at such a time, you were to sight the moon with one straight stick or instrument, and at the same moment I were

to sight the sun (through smoked glass) with another stick laid across yours, the angle between the two sticks would be, would it not, one acute angle of the right-angled triangle which has the sun at the other acute angle and the moon at the right angle? So when we have measured the angle between our two sticks, we can chart this great triangle, could we not?"

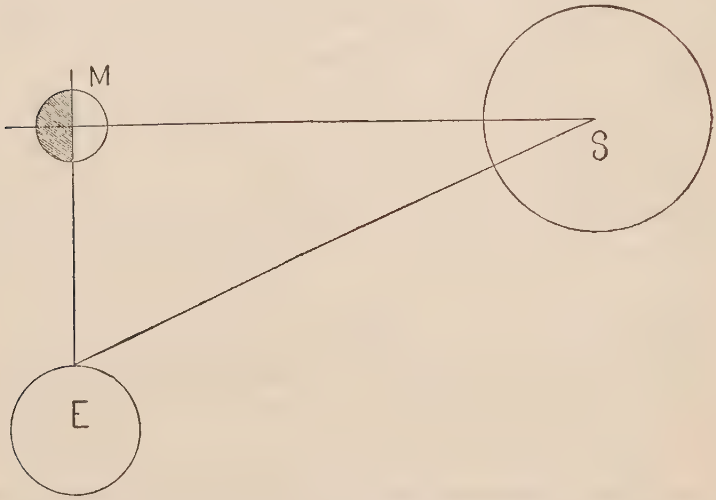

FIG. 5.—Diagram to Show How Aristarchus Measured the Sun's Distance.

"I see at once that we could do that, and so get the shape of the triangle, but should we know anything about its size?"

"Not at first. But we could see at once that the line between the sun and the moon is longer than the line from the moon to the earth, and could estimate the exact proportion between these distances. Is it not so?"

"Clearly. We need only extend the line of the sticks to form the hypotenuse of the triangle."

"And that would be an important beginning. If, then, we could

find out how far we are from the moon, we could readily compute, with the aid of our triangle, the distance of the sun, and from that, the size of the sun, compared with the moon and the earth."

"I can see that it must be so, but it seems very astonishing to think that such things could be learned merely from crossing two sticks."

"So it surely does. And that is why this test, as Aristarchus made it, is a wonderful experiment. But of course the determining of the angle between the sticks, though it is the key to the whole problem, does not by itself suffice. We must use knowledge gained from eclipses to give us clues to the relative sizes of the earth and moon, and the distance of the moon from the earth, in terms of the earth's diameter."

"And has Aristarchus done all this?"

"Yes; he has made these computations, and many others. He found the angle of the crossed sticks to be an angle of eighty-seven degrees, and from this charted a triangle which shows the sun to be eighteen times as far away from the earth as is the moon. This makes the sun several thousand times larger than the moon, and perhaps three hundred times the size of the earth."

"That seems quite impossible," said the youth, marvelling.

"Not impossible, certainly," the Master corrected. "But widely at variance with the opinions that have usually been held. Those opinions, however, have been mostly mere guesses, and the computations of Aristarchus, you must remember, are founded on experiment. It is because it all seems so startling that I have thought it might be of interest for us to make the experiment of measuring the angle with the crossed sticks for ourselves. We shall use, of course, the quadrant with which you have seen

me measure angles between stars. I think it may be a more accurate instrument than any that Aristarchus had. In that case, we may, perhaps, improve on his measurements, and better his conclusions. But in any event, we shall be able to do something that he could not do—we shall be able to calculate the distances (earth to moon, earth to sun, and all the rest), as well as the sizes of moon and sun, in terms of actual stadia; whereas he could only calculate in terms of *relative* distances and dimensions. Do you recall why we have this advantage?"

"To be sure. It is because you have measured the actual size of the earth, which no one knew before," the youth responded instantly. "And I saw you do it," he added proudly.

"Then you see how one experiment fits into another," said the Master. "And how an observation may have unexpected bearings. You may recall my saying that to know the exact size of the globe might be of no great consequence, since we can live on only a small part of it. But now we see that knowledge of the size of the earth leads to knowledge of the moon and the sun as well —telling us new things about the universe. And that, if not of immediate practical importance, is at least of great human interest."

"To me," said Hipparchus (who was destined to become himself a distinguished astronomer, and the father of one yet more famous), "to me, the study of the sun and moon and planets seems the most interesting thing in all the world. I shall count the hours impatiently till the moon is at the half, and I can watch you make this wonderful experiment. It will be like seeing a miracle performed."

"It is indeed a wonderful experiment," said Eratosthenes. "And you must not fail to remember that it was not I, but Aristarchus

of Samos, who devised it. It seems a simple observation. Yet I think we should not be far wrong in estimating it—in view of its far-reaching implications—one of the most amazing demonstrations ever given of the inventive fertility of the human intellect."

With that verdict, we of a later epoch—recalling that about seventeen hundred years were to elapse before men should again appear who would even attempt to catch intellectual step with the old Greek—can most heartily agree. But at the same time we must appraise the path-breaking work of Eratosthenes himself, who first measured the earth, as entitled to stand side by side with the achievement of his slightly older contemporary, the first sun-measurer.

Both men were amazing geniuses, gifted with that rarest of human endowments, creative imagination.

II

FORERUNNERS OF ERATOSTHENES

THE city of Alexandria, where Eratosthenes made his famous measurement, was situated at the mouth of the Nile. But only in a geographical sense was it an Egyptian city. It had been founded about a century before by Alexander the Great, and it had present importance because it was the seat of government of Alexander's general (and putative half-brother) Ptolemy, who

made himself king of the African portion of the great Macedonian's empire.

Ptolemy had been with his chief in the east, and was with him in Babylon when he died. He had therefore come personally in contact with the Babylonian civilization. Without doubt this had a most important influence upon him, and through him upon the new civilization of the west.

In point of culture, Alexandria must be regarded as the successor of Babylon, scarcely less directly than of Greece. Ptolemy himself was, of course, a Macedonian, and therefore, from the Athenian standpoint, hardly better than a barbarian. But he counted himself a Greek. And the city which his chief had founded and which became his capital, has always been accounted a Greek city.

Following the Babylonian model, Ptolemy erected a vast museum and began collecting a library. Before his death it was said that he had collected no fewer than 200,000 manuscripts. He had gathered also a company of great teachers, and founded a school of science which made Alexandria the culture-center of the world.

This work, in all its cultural aspects, was carried forward energetically by Ptolemy Philadelphus, son and successor of the founder of the dynasty, and by the succeeding descendants who for some centuries maintained the glory of the principality and made the name of Ptolemaic Egypt a synonym for oriental splendor no less than for Grecian culture.

Eratosthenes as Librarian

Under the second and third Ptolemies, the library grew. It is said to have attained ultimately 700,000 volumes. Ancient figures may always be taken with due allowance, but there can be no

question that the famous library of the Ptolemies was the greatest collection of books anywhere got together in ancient times.

Doubtless it was also one of the most cosmopolitan of libraries. Papyrus scrolls of Egypt in hieratic writing must have mingled with parchment scrolls of Greece, and with copies of Babylonian records, if not the original inscribed clay tablets themselves. Not unlikely there were also records from the farther east—from Persia, India, even China. It was recorded that Alexander had sent back treasures from the far east, and the pupil of Aristotle was not likely to overlook written records among the rest. These would gravitate naturally to Alexandria, when that became the culture-center of the world.

Eratosthenes, who was born in upper Egypt, came to Alexandria to be the custodian of books in the great library. The nickname "Beta" (the second) given him implies that he was one of the most learned of men, being accounted at worst second to the acknowledged leader in many departments of thought and research. That he should be primarily a geographer, in the age when the almost fabulous conquering pilgrimage of Alexander had fixed the attention of the western world on geography, was almost a matter of course. The use we have seen him make of his geographical—combined with astronomical—knowledge clearly enough shows that he was no mere pedant, but a man of practical genius.

The official librarian of the greatest collection of books in the world may well be supposed to have been among the most indefatigable of readers. No doubt he was familiar with the languages in which the chief books of the collection were inscribed. And his taste for geography and astronomy would naturally lead

him to make himself master of the contents of all leading works on these subjects.

Thus he must have become thoroughly familiar with whatever had been recorded in Egypt and Babylonia on every aspect of astronomy.

It is interesting to attempt, in a vague general way—nothing beyond that being possible—to reconstruct the antique conceptions of the heavens as they must have presented themselves to the custodian of books in the Alexandrian library there toward the latter part of the third century before our era.

It excites one's envy to reflect on the hundreds of volumes that lay before him, whose existence is known to us of a later day only by chance references, or is known not at all. There were other works, however, that were destined to be preserved, wholly or in part, or the import of which is known with reasonable certainty from excerpts made by writers whose productions were fortunate enough to escape the ravages of the subsequent period.

At best, however, one feels a sense of futility in attempting to reconstruct the astronomical knowledge and cosmologic speculations of the generations preceding the time of Eratosthenes, when individual observers appear, from our distant view, as at best half-mythical characters, regarding whose attainments the transcribed records are often contradictory and almost always more or less doubtful.

Even of Aristarchus of Samos, the Copernicus of antiquity, whose life perhaps overlapped that of Eratosthenes, we know almost nothing beyond the fact that he lived at Samos, an island at the eastern end of the Mediterranean, and wrote a treatise on measuring the distance of the sun that has been preserved. The more important fact that he conceived the sun to be the center of

the universe, with the world revolving about it, has come down to posterity largely by a chance utterance of the great geometer Archimedes.

That testimony, with a few other rumors, suffices to establish the fact that Aristarchus held this view, which to his contemporaries must have seemed utterly fantastic. But what would we not give to be able to peruse his own discussion of this revolutionary doctrine, as doubtless Eratosthenes was able to do there in the Alexandrian library.

But, for the matter of that, the same futile wish comes with mention of almost every one of the great Greek predecessors of Eratosthenes, with whose names are associated the successive stages of advance in astronomical knowledge that led up from the old Oriental conception of the world as a flat disk afloat on primordial waters, to the Pythagorean conception of the round world—even perhaps a moving world—which Aristotle accepted, and which led to the culminating conception of Aristarchus.

Thales, First Greek Astronomer

Briefly summarized, the Greek achievements may be listed in some such order as this:

First came Thales, oldest of Greek philosophers, whose popular fame was derived from his supposed prediction of an eclipse, as recorded by Herodotus. Thales lived in Asia Minor, in close contact with the Babylonian civilization, and doubtless his knowledge of astronomy was gained at second hand, at least very largely, from the Babylonian records.

His great contribution to the method of the future astronomer was the development of the principle of triangulation, through which the distance of any body may be determined from measurement of a base line and of the two angles at the corners of the triangle.

For Thales, the earth remained a flat disk, after the Babylonian model. There are, indeed, contradictory rumors, but there seems no adequate ground for supposing that he attained the conception of a round world.

Pythagoras and Anaxagoras

That conception was attained by philosophers of the school of Pythagoras, out in Italy. Pythagoras himself, like his successor Aristarchus, was a native of the Island of Samos, but he migrated to Italy, and he is chiefly remembered as the founder of the Italic School. It is somewhat in dispute whether Pythagoras himself or one of his followers, Parmenides or Philolaus, originated and chiefly taught the doctrine of the round earth. But at all events that conception is ascribed to the Pythagorean School.

So far as we know, this doctrine of the round earth was a brand new conception, never attained by any earlier astronomer or cosmologic dreamer. It is the preeminent contribution of Greece to a true conception of cosmology.

It stopped far short, however, of the true conception of the rotating and revolving world.

Aristarchus, as we have seen, attained even to that height, but his voice was unheeded in his own generation, and utterly ignored for about seventeen centuries afterward.

The other notable Greek contributions were the conception of Anaxagoras, the Clazomenean philosopher who was ultimately banished from Athens for his iconoclasm, that the sun is really a great ball of molten iron and that eclipses are due to the shadow of the earth on the moon. His contributions further included a true interpretation of the moon's phases, and the sagacious guess that the Milky Way is composed of vast numbers of minute stars, which owe their characteristic appearance to the earth-shadow

cast on them by the sun when it is passing on the under side of the world.

Of course the shadow part of this theory was fantastic, though it would not seem so were we to suppose, as Anaxagoras and his contemporaries did, that the vault of the firmament is at a comparatively short distance from the earth.

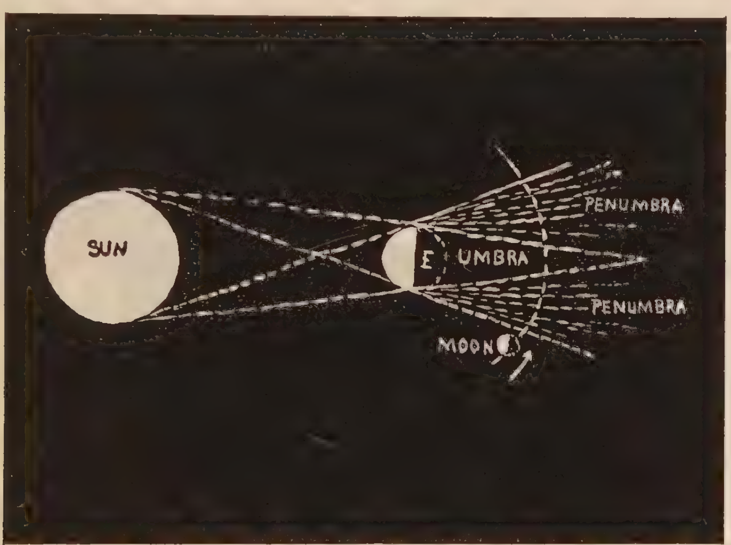

FIG. 6.—An Eclipse of the Moon, as Correctly Conceived by Anaxagoras.

The Epicycles of Eudoxus

For the rest, the system of epicycles of Eudoxus, which attempted to explain the curious movements of the sun and planetary bodies, may be taken as the final contribution of Greek thought to cosmology prior to the time of Aristarchus.

This scheme consisted essentially of the invention of an elaborate series of imaginary spheres which revolved and carried sun, moon, and the various planets with them in a way to account, after a fashion, for the observed movements of these bodies.

We shall learn something more of these epicycles in a modified form, a little later. Here it suffices that the scheme of Eudoxus was accepted by Aristotle, and elaborated at least with his co-operation to comprise fifty-five different spheres of revolution, and that this doctrine, fantastic to modern eyes, was to keep grip on the cosmologic dreamers of Europe for a term of more than two thousand years.

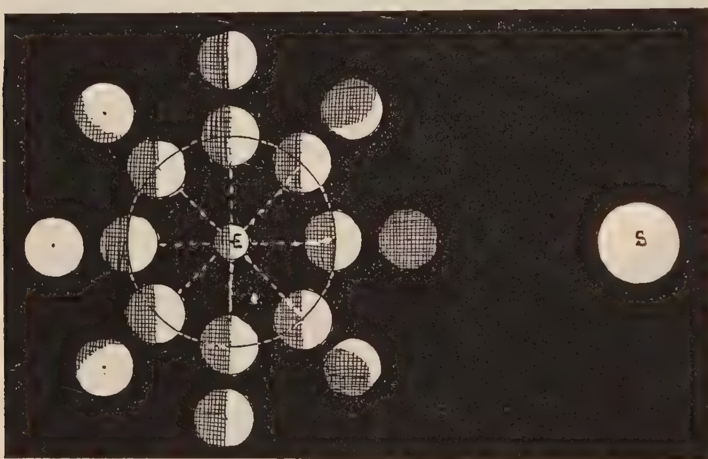

FIG. 7.—The Moon's Phases as Correctly Interpreted by Anaxagoras and Subsequent Greeks.

What did wise old Eratosthenes, the librarian, think of these fantastic epicycles of his Greek precursor?

We do not know. We know only that he accepted the sphericity of the earth as beyond cavil—else he would not have measured it.

One has a feeling that so practical a man would look askance at a system which cobwebbed the sky with imaginary circles. But one cannot know. After all, the epicycles did explain the astronomical phenomena, and we shall see how completely a

similar conception—indeed only a modified conception—dominated the mind of the great Hipparchus, the successor of Eratosthenes.

We shall see also in due course that the same conception was dominant throughout the astronomical world for more than a thousand years thereafter.

Indeed, it had assured place in science, as the only plausible explanation of the observed phenomena of the heavens, until the remote successor of Aristarchus, the illustrious Copernicus, should come to transform the world's conception of the essential scheme of the planetary system which for the ancients was the universe.

Antiquity of Egyptian Astronomy

But the Greek conceptions of the cosmos were perhaps less insistently before the mind of the Alexandrian librarian than the far more ancient Oriental conceptions, as recorded in the archives of Egyptian and Babylonian lore.

We must not forget that the Greeks, in the eyes of Egyptians and Babylonians, were parvenus.

"O Solon," said the Egyptian priest when the wise man of Greece visited him, "O Solon, you Greeks are but children."

And why should he not speak thus, when we reflect that Greek civilization, in that sixth century before our era, was not far from its beginnings, whereas the Egyptians stood in the shadow of pyramids and temples that represented a civilization three thousand, perhaps four thousand, years earlier—a period far more remote from the sixth century B.C., than that century is from our own time?

How shall one attempt to summarize the astronomical knowledge, the cosmologic speculations, of a civilization spread across such an abysm of time?

We know that the pyramid-builders were astronomers, at what

we speak of as "the dawn of history," about four thousand years before the beginning of the Christian era. We know this because there are sloping tunnels in the pyramids that can be accounted for only on the supposition that they were designed to make visible from the depths of the pyramid itself a particular star, which at that time was the pole star.

We know too that there are other channels, and also corridors in some of the great temples, which appear to be oriented for observation of the rising or setting of the sun on the day of the summer solstice.

We know further that the Egyptians very early recognised that their year of twelve thirty-day months did not correspond exactly with the solar cycle, and were led to introduce an extra period of five days—a "little month" between the end of the twelfth month and the new year.

This did not quite solve the problem of adjusting the calendar to the true year, but the shift of seasons that resulted was so slow that it probably was not thought of as an inconvenience. Meantime the fact of early recognition of the approximate length of the true year in itself connotes a certain stage of astronomical development.

Again, we know that the Egyptians early noted the apparent eastward movement of the sun in a restricted course across the heavens, and were led to name and number the constellations of the zodiac.

Their fantastic conceptions of animal forms as imaginary figures scrolling the firmament were transmitted to the Greeks, and have come down to us not greatly modified. Absurd as they are, they have seemed a convenience to the amateur star-gazers of all generations.

It is obvious that the development of these imaginary boundaries of the star groups implies careful study of the positions of the stars themselves.

The Egyptian Interpretation of the Heavens

Naturally the question arises as to what interpretation the Egyptians put upon the heavens they scrutinized. The question is by no means easy to answer. One doubts whether old Eratosthenes, there in his library, with a wealth of material at hand,

FIG. 8.—Egyptian Conception of the Separation of the Heavens From the Earth. (Redrawn from Maspero's *Dawn of Civilization.*)

and with opportunity to consult the astronomer-priests of his time as well, could have answered the question with any degree of finality.

Consider in the first place that we have to do with the opinions and beliefs not of a single generation, but of perhaps twelve hundred generations of men, even counting only from the time of the pyramid-builders.

The star-gazers of Egypt were priests, and astronomy was a sacerdotal function. Therefore we may suppose that interpreta-

tions of the heavens, once made, were not readily abandoned. Still it must be recognised that even the ecclesiastic mind can change, at least as to details of interpretation, and perhaps even more than once, in twelve hundred generations.

So when we ask what was the Egyptian interpretation of the heavens, we ask a question impossible of explicit answer.

About the most that can be hoped for is to gain an inkling of the Egyptian interpretation of the heavens in the later day when the Greeks had attained a stage of civilization at which they could record their own ideas, and contrast them with the ideas of contemporary nations with which they came in contact.

Coupled with this we have the hieroglyphic records of the Egyptians themselves, which moderns have learned to interpret. But these are religious records, and scholarship is incapable of interpreting, with any large degree of certitude, the religious beliefs of an alien people.

Suppose the hypothetical visitor from Mars to whom we are always appealing were to set out to interpret the religious beliefs of the inhabitants of Christendom in the 20th century. When he had read the sacred books, compiled lists of what appeared to him to be deities from the Hagiologies, racked his brain over the differences that separated the devotees of some scores of sects, each viewing the inspired testimonials from a different angle—what, think you, is likely to be the validity of the report he will make?

Correspondingly valid, I take it, is the interpretation that we are likely to make of the records which seem to tell of hierarchies of gods of high and low degree in the Egyptian Pantheon.

We are asked to believe that the Egyptians thought the sun to be the abode of one of the major gods, who progressed along

a celestial river, and battled the god of darkness. We are told that the celestial river was connected with the Nile at its source, that the sun-god came nearer to Egypt in the summer because then the river overflowed, even as the Nile did, and the god of a preference kept as near as possible to the hither bank of the stream.

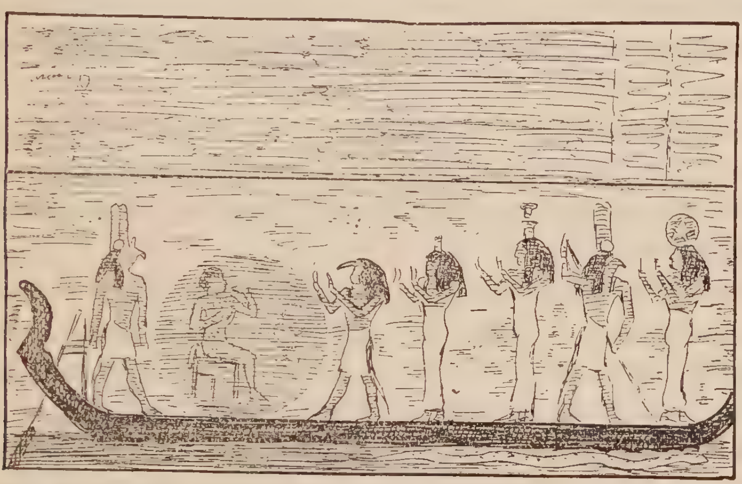

FIG. 9.—Egyptian Conception of the Sun Embarking on His Daily Journey Through Egypt. (Redrawn from Rosellini's *Monumente Del Culto.*)

We are told too that the stars were regarded as celestial hosts, each one either a sort of lantern carried by the spirit of a minor deity, or itself constituting such a deity.

The planets, of course, were the abiding-places of yet other deities. These in particular concerned themselves with the affairs of men, and foretold human events—though astrology apparently did not attain the position in Egypt that it held in Mesopotamia.

But when we ask just what degree of literalness is implied in these interpretations, no satisfactory answer is forthcoming.

Probably the rank and file of the Egyptians accepted such interpretations literally, just as the rank and file of moderns accept literally the conventional interpretation of sundry of their cabalistic rituals. But one greatly doubts whether the astronomer-priests who generation after generation studied the stars, and acquired the knowledge of the movements of the heavenly bodies implied in their records, regarded the crude anthropomorphisms that they served out to the people as other than symbols.

The Egyptian Cosmology

Be that as it may, however, there is perhaps no reason to doubt that even the wisest of the astronomer-priests had very crude notions indeed as to the actual structure of the cosmic mechanism.

We may be certain that they regarded the stars as mere sparks or candle-flames of light, placed in the firmament either to delight the eye of man or in some other way to serve his purposes. There is probably no doubt that they regarded the earth as an oblong structure (the Nile Valley being, of course, the model) and the vault of the heavens as a literal cover of metal or glass, supported at the corners either by mountains or pillars of indeterminate character.

That this box-like earth is the center of the universe—the one big, all-important structure in the universe—was of course never called in question. That is an obvious truth, which we may suppose astronomer-priests and people alike took for granted.

The conception that the earth is a subordinate structure in the cosmic mechanism; that the sun is a gigantic body at the center of the planetary system; and that the stars are in reality suns —these conceptions would no more have occurred to the mind

of the astronomer-priests, even at a period two or three thousand years this side the time of the pyramid-builders, than it would occur to the mind of a modern child.

But that thought, of course, was equally alien to the mind of any Greek or Babylonian of the period—with the sole exception, so far as there is any record or reminiscence, of the strangely anachronistic sun-measurer, Aristarchus of Samos: a man whose mental isolation in his day and generation must have been greater than that of any other man known to history or tradition.

The Astronomy of Babylonia

If old Eratosthenes, there in the Alexandrian library, consulted the records which Alexander had caused to be transmitted from Babylonia, he would find that the inhabitants of Mesopotamia—who could boast a civilization perhaps antedating that of Egypt itself—had developed a coterie of astronomer-priests in many ways comparable to that of the Egyptians.

The most obvious difference he would observe, perhaps, would be that the Babylonians seemed to place the moon-god at the head of the hierarchy, instead of the sun-god. It would appear, too, that in Mesopotamia the astronomer-priests paid special attention to the number of the planetary bodies. Counting them in order, moon, sun, Mercury, Venus, Mars, Jupiter, and Saturn, these are seven.

And because they are seven, the very ancient astronomer-priests of Babylonia had come to ascribe a particular sacredness to that number.

In the Babylonian writings, and in the writings of the allied nation occupying a part of the territory between Egypt and Mesopotamia, there would be found perpetually recurring references to the sacred number seven. It would be obvious that the seven planetary deities held a place of peculiar consequence

amidst the three hundred spirits of heaven and the six hundred spirits of earth which could be tabulated from what might be spoken of as Babylonian hagiology.

That these seven planets were peculiarly associated with the prognostication of human events was everywhere apparent.

FIG. 10.—Babylonian Clay Table Representing a Map of the World. (Redrawn from Maspero.)

At the outset, each planet presided over one day of the week —there being, indeed, a seven-day week for the sole reason that the number of planets was seven. For the same reason, the sacred tablets told of seven days of creation, and there were recurring references to seven years of plenty, seven abominations, seven last plagues, seven golden candlesticks, seven sons, seven angels, a seven-headed dragon with seven crowns, seven spirits of God.

It would be noted, too, that profoundly important matters of sacred ritual were of the same astronomical origin. Over and over it was repeated that seven bullocks, seven rams, seven lambs without blemish—in each case one for each planetary deity—should be used in preparing the savory meat-offerings.

To Eratosthenes such ideas must have seemed fantastic. Inheritor of the rationalistic traditions of such forebears as Anaxagoras, Anaximander, and a host of others, the man who had measured the round world must have looked with amusement and pity on such childish traditions, even as he looked upon the associated cosmologic schemes of the Babylonians, according to which the earth is a flat disk, with mountains at its borders, surrounded by an interminable ocean.

Himself a poet, he must have read with interest, even with pleasure, the poems that enshrine the cosmologic and cosmogonic guesses of the Asiatic Orientals. But the part of him that was geographer rather than poet must have shrugged shoulders at those passages which told of the flat earth resting on an infinite ocean or (in other versions) supported by pillars.

Whether he viewed in the same light passages which told of the creation of the solid vault of the firmament before the earth itself was created, and of the creation of the sun, moon and planets on a subsequent day (and "the stars also" as an afterthought), we can only surmise. For though we know that the earth-measurer had a true conception as to the form and size of the globe, we have no clear record as to what were his views of the mechanism of the heavens.

Let us leave the great earth-measurer in his library, amidst literary treasures that modern eyes are not privileged to see.

III

HIPPARCHUS, "THE LOVER OF TRUTH"

ERATOSTHENES outlived most of his great contemporaries. He saw the turning of that first and greatest century of Alexandrian science, the third century before our era.

He died in the year 196 B.C., having, it is said, starved himself to death to escape the miseries of blindness;—to the measurer of shadows, life without light seemed not worth the living.

The great geographer-astronomer left no immediate successor. A generation later, however, another great figure appeared in the astronomical world in the person of Hipparchus, a man who, as a technical observer, had perhaps no peer in the ancient world: one who set so high a value upon accuracy of observation as to earn the title of "the lover of truth."

Hipparchus was born at Nicaea, in Bithynia, in the year 160 B.C. His life, all too short for the interests of science, ended in the year 125 B.C. The observations of the great astronomer were made chiefly, perhaps entirely, at Rhodes. A misinterpretation of Ptolemy's writings led to the idea that Hipparchus performed his chief labors in Alexandria, but it is now admitted that there is no evidence of this. Delambre doubted, and most subsequent writers follow him here, whether Hipparchus ever so much as visited Alexandria.

In any event there seems to be no question that Rhodes may claim the honor of being the chief site of his activities.

Hipparchus was credited with an epigram of rather dubious import, to the effect that his great predecessor, Eratosthenes,

approached astronomy from the standpoint of the geographer, and geography from the standpoint of the astronomer.

It is not quite clear that this was intended as criticism, though commonly so interpreted. In any case, no counter-charge in kind could be made against the critic himself; he was an astronomer pure and simple. His gift was the gift of accurate observation rather than the gift of imagination.

No scientific progress is possible without scientific guessing, but Hipparchus belonged to that class of observers with whom hypothesis is held rigidly subservient to fact.

It was not to be expected that his mind would be attracted by the heliocentric theory of Aristarchus. He used the facts and observations gathered by his great predecessor of Samos, but he declined to accept his theories. For him the world was central; his problem was to explain, if he could, the irregularities of motion which sun, moon, and planets showed in their seeming circuits about the earth.

Hipparchus had the gnomon of Eratosthenes—doubtless in a perfected form—to aid him, and he soon proved himself a master in its use.

Accuracy of observation was everything: that alone could lead to success.

The Sun's Eccentricity

Perhaps his greatest feat was to demonstrate the eccentricity of the sun's seeming orbit.

We of to-day, thanks to Kepler and his followers, know that the earth and the other planetary bodies in their circuit about the sun describe an ellipse and not a circle. But in the day of Hipparchus, though the ellipse was recognized as a geometrical figure (it had been described and named along with the parabola and hyperbola by Apollonius of Perga, the pupil of Euclid),

yet it would have been the rankest heresy to suggest an elliptical course for any heavenly body.

A metaphysical theory, as propounded perhaps by the Pythagoreans but ardently supported by Aristotle, declared that the circle is the perfect figure, and pronounced it inconceivable that the motions of the spheres should be other than circular. This thought dominated the mind of Hipparchus, and so when his careful measurements led him to the discovery that the northward and southward journeyings of the sun did not divide the year into four equal parts, there seemed nothing open to him but to assume that the earth does not lie precisely at the center of the sun's circular orbit.

In point of fact, the sun (reversing the point of view in accordance with modern discoveries) does lie at one focus of the earth's elliptical (nearly circular) orbit, and therefore away from the physical center of that orbit.

In other words, the observations of Hipparchus were absolutely accurate. He was quite correct in finding that the sun spends more time on one side of the equator than on the other.

When, therefore, he estimated the relative distance of the earth from the geometrical center of the sun's supposed circular orbit, and spoke of this as the measure of the sun's eccentricity, he propounded an idea in which true data of observation were curiously mingled with a positively inverted theory.

That the theory of Hipparchus was absolutely consistent with all the facts of this particular observation is the best evidence that could be given of the difficulties that stood in the way of a true explanation of the mechanism of the heavens.

The Sun on a Cart-wheel

But it is not merely the sun which varied in the speed of its orbital progress; the moon and the planets also show curious

accelerations and retardations of motion. The moon in particular received most careful attention from Hipparchus.

Dominated by his conception of the perfect spheres, he could find but one explanation of the anomalous motions which he observed, and this was to assume that the various heavenly bodies do not fly on in an unvarying arc in their circuit about

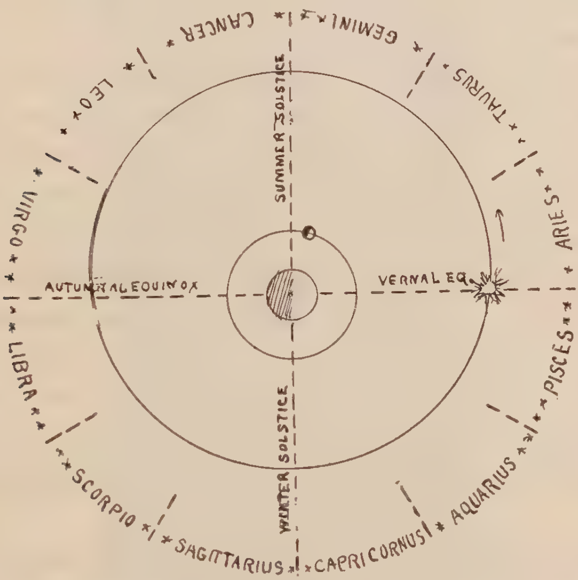

FIG. 11.—The Seasons According to Hipparchus. The Orbit of the Sun is Circular, but the Earth is not at the Center. Note the Constellations of the Zodiac.

the earth, but describe minor circles as they go which can be likened to nothing so tangibly as to a light attached to the rim of a wagon-wheel in motion.

If such an invisible wheel be imagined as carrying the sun, for example, on its rim, while its invisible hub follows unswervingly the circle of the sun's mean orbit (this wheel, be it under-

stood, lying in the plane of the orbit, not at right-angles to it), then it must be obvious that while the hub remains always at the same distance from the earth, the circling rim will carry the sun nearer the earth, then farther away, and that while it is traversing that portion of the arc which brings it towards the earth, the actual forward progress of the sun will be retarded notwithstanding the uniform motion of the hub, just as it will be accelerated in the opposite arc.

Now, if we suppose our sun-bearing wheel to turn so slowly that the sun revolves but once about its imaginary hub while the wheel itself is making the entire circuit of the orbit, we shall have accounted for the observed fact that the sun passes more quickly through one-half of the orbit than through the other.

Moreover, if we can visualize the process and imagine the sun to have left a visible line of fire behind him throughout the course, we shall see that in reality the two circular motions involved have really resulted in producing an elliptical orbit.

The idea is perhaps made clearer if we picture the actual progress of a lantern attached to the rim of an ordinary cart-wheel.

When the cart is drawn forward the lantern is made to revolve in a circle as regards the hub of the wheel, but since that hub is constantly going forward, the actual path described by the lantern is not a circle at all but a waving line. It is precisely the same with the imagined course of the sun in its orbit, only that we view these lines just as we should view the lantern on the wheel if we looked at it from directly above and not from the side.

The proof that the sun is describing this waving line, and therefore must be considered as attached to an imaginary wheel,

is furnished, as it seemed to Hipparchus, by the observed fact of the sun's varying speed.

That is one way of looking at the matter. It is an hypothesis that explains the observed facts—after a fashion, and indeed

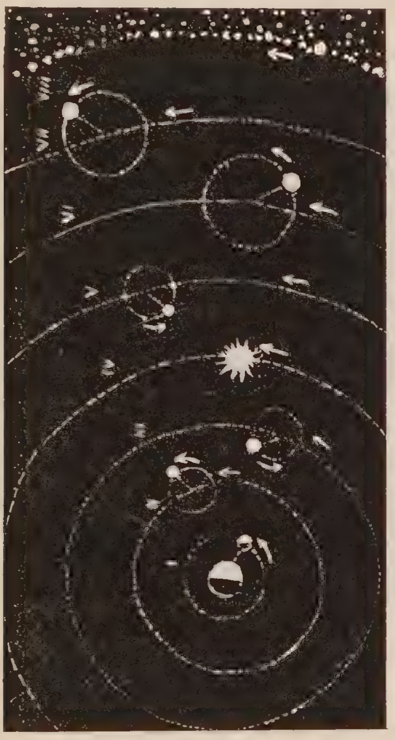

FIG. 12.—The Epicycles of Hipparchus.
(Compare with Fig. 13.)

a very remarkable one. The idea of such an explanation did not originate with Hipparchus. The germs of the thought were as old as the Pythagorean doctrine that the earth revolves about a center that we cannot see. Eudoxus, as we saw, gave the conception greater tangibility, and may be considered as the father

of this doctrine of wheels—epicycles, as they came to be called. We saw, too, that the cartwheel scheme of the universe had the sanction of Aristotle himself.

As new irregularities of motion of the sun, moon, and planetary bodies were pointed out, new epicycles were invented. There is no limit to the number of imaginary circles that may be in-

FIG. 13.—True Explanation of Seemingly Looped Orbit of an Outer Planet. *Inner Circle*, Earth's Orbit. *Outer Circle*, Orbit of Mars. *Looped Line*, the Apparent Course of Mars, as Projected Against the Stationary Stars. Cause: the Earth's More Rapid Revolution.

scribed about an imaginary centre, and if we conceive each one of these circles to have a proper motion of its own, and each one to carry the sun or planet in the line of that motion, except as it is diverted by the other motions—if we can visualize this complex mingling of wheels—we shall certainly be able to imagine the heavenly body which lies at the juncture of all the rims,

as being carried forward in as erratic and wobbly a manner as could be desired.

In other words, the theory of epicycles will account for all the facts of the observed motions of all the heavenly bodies, but in so doing it fills the universe with a most bewildering network of intersecting circles.

Even in the time of Aristotle, it will be recalled, fifty-five of these spheres were computed.

We may well believe that the clear-seeing Aristarchus would look askance at such a complex system of imaginary machinery. But Hipparchus, pre-eminently an observer rather than a theorizer, seems to have been content to accept the theory of epicycles as he found it, though his studies added to its complexities.

And Hipparchus was the dominant scientific personality of his century. What he believed became as a law to his immediate successors.

His tenets were accepted as final by their great popularizer, Ptolemy, two centuries later; and so the heliocentric theory of Aristarchus passed under a cloud almost at the hour of its dawning, there to remain obscured and forgotten for the long lapse of centuries.

A thousand pities that the greatest observing astronomer of antiquity could not, like one of his great precursors, have approached astronomy from the standpoint of geography and poetry.

Had he done so, perhaps he might have reflected, like Aristarchus before him, that it seems absurd for our earth to hold the giant sun in thraldom. Then perhaps his imagination would have reached out to the heliocentric doctrine, and the cobweb hypoth-

esis of epicycles, with that yet more intangible figment of the perfect circle, might have been wiped away.

Authority Versus Progress

But it was not to be. With Aristarchus the scientific imagination had reached its highest flight; but with Hipparchus it was beginning to settle back into regions of foggier atmosphere and narrower horizons.

For what, after all, does it matter that Hipparchus should go on to measure the precise length of the year and the apparent size of the moon's disk; that he should make a chart of the heavens showing the place of 1080 stars; even that he should discover the precession of the equinoxes;—what, after all, is the significance of these details as against the all-essential fact that the greatest scientific authority of his century—the one truly heroic scientific figure of his epoch—should have lent all the forces of his commanding influence to the old, false theory of cosmology, when the true theory had been propounded and when he, perhaps, was the only man in the world who might have substantiated and vitalized that theory?

It is easy to overestimate the influence of any single man, and, contrariwise, to underestimate the power of the *Zeitgeist*. But when we reflect that the doctrines of Hipparchus, as promulgated by Ptolemy, became, as it were, the last word in astronomical science for both the Eastern and Western worlds, and so continued after a thousand years, it is perhaps not too much to say that Hipparchus, "the lover of truth," missed one of the greatest opportunities for the promulgation of truth ever vouchsafed to a devotee of pure science.

New Measurements

But all this, of course, detracts nothing from the merits of Hipparchus as an observing astronomer.

A few words more must be said as to his specific discoveries

in this field. According to his measurement, the tropic year consists of 365 days, 5 hours, and 49 minutes, varying thus only 12 seconds from the true year, as the modern astronomer estimates it.

Yet more remarkable, because of the greater difficulties involved, was Hipparchus's attempt to measure the actual distance of the moon. Aristarchus had made a similar attempt before him. Hipparchus based his computations on studies of the moon in eclipse, and he reached the conclusion that the distance of the

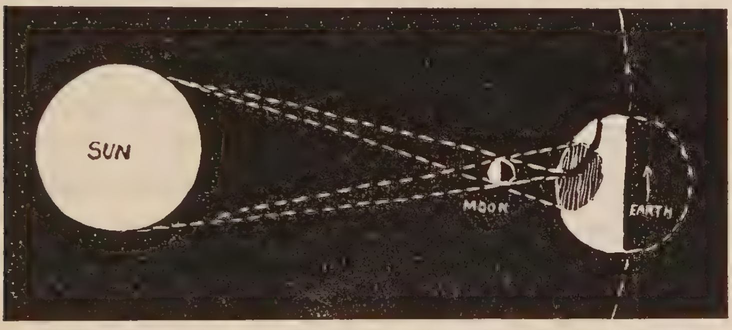

FIG. 14.—An Eclipse of the Sun, Clearly Understood by Hipparchus.

moon is equal to 59 radii of the earth (in reality it is 60.27 radii).

Here, then, was the measure of the base-line of that famous triangle with which Aristarchus had measured the distance of the sun.

Hipparchus must have known of that measurement, since he quotes the work of Aristarchus in other fields. Had he now but repeated the experiment of Aristarchus, with his perfected instruments and his perhaps greater observational skill, he was in position to compute the actual distance of the sun in terms

not merely of the moon's distance but of the earth's radius. And now there was the experiment of Eratosthenes to give the length of that radius in precise terms.

In other words, Hipparchus might have measured the distance of the sun in stadia.

But if he had made the attempt—and, indeed, it is more than likely that he did so—the elements of error in his measurements may still have kept him wide of the true figures.

A New Star

The chief studies of Hipparchus were directed, as we have seen, towards the sun and the moon, but a phenomenon that occurred in the year 134 B.C. led him for a time to give more particular attention to the "fixed" stars.

The phenomenon in question was the sudden outburst of a new star; a phenomenon which has been repeated now and again, but which is sufficiently rare and sufficiently mysterious to have excited the unusual attention of astronomers in all generations.

Modern science offers an explanation of the phenomenon, as we shall see in due course. We do not know that Hipparchus attempted to explain it, but he was led to make a chart of the heavens, probably with the idea of guiding future observers in the observation of new stars. Here again, Hipparchus was not altogether an innovator, since a chart showing the brightest stars had been made by Eratosthenes; but the new charts were much elaborated.

The studies of Hipparchus led him to observe the stars chiefly with reference to the meridian rather than with reference to their rising, as had hitherto been the custom.

In making these studies of the relative position of the stars, Hipparchus was led to compare his observations with those of

the Babylonians, which, it was said, Alexander had caused to be transmitted to Greece. He made use also of the observations of Aristarchus and others of his Greek precursors. The result of his comparisons proved that the sphere of the fixed stars had apparently shifted its position with reference to the plane of the sun's orbit—that is to say, the plane of the ecliptic no longer seemed to cut the sphere of the fixed stars at precisely the point where the two coincided in former centuries. The plane of the ecliptic must therefore be conceived as slowly revolving in such a way as gradually to circumnavigate the heavens.

This important phenomenon is described as the precession of the equinoxes.

Precession Explained

This phenomenon consists of a slow westward movement of the point of intersection of the imaginary line of the sun's course in the celestial sphere with the imaginary extended plane of the earth's equator,—that is to say, of the equinoctial point.

It is a matter of supreme importance to the astronomer, because the longitudinal position (so-called Right Ascension) of the stars is calculated from this point, or rather from the meridian passing through this point—just as terrestrial longitude is calculated from the meridian of Greenwich.

Celestial longitude, or Right Ascension, is calculated all in one direction, eastward, throughout 360 degrees, instead of counting in both directions, to meet at meridian 180 half-way round, but the principle is the same. The shift of the equinoctial point, or zero meridian, makes the stars year by year change their longitude, or Right Ascension.

The amount is less than one minute of arc per year (50.10 seconds, to be accurate), but the cumulative effect in a long term of years is notable.

Since the formation of the earliest catalogue to be preserved (the catalogue of Hipparchus) the place of the equinox has retrograded about 30 degrees—equivalent to something like sixty apparent diameters of the moon. A star-catalogue, therefore, is accurate only for the period in which it is made. But the relative positions of the stars do not change, and the value of an old catalogue is at once restored by applying the same correction to all star-longitudes.

It will be understood, of course, that the actual cause of precession is not the movement of the star-vault, but the slow, even swing of the earth as its axis, without changing its angle of slope as regards the ecliptic, swings about, describing a cone of such dimensions that its completion takes place only in a period of almost 26,000 years (25,868).

The effect will be best understood if one thinks of an ordinary top, spinning with its axis tipped at an angle of about twenty-three degrees with the level surface, say a table-top, on which its point rests. Observe the top of the axis describe a circle, while the point of support on the table does not move. If the table-top is regarded as the plane of the ecliptic, and the rim of the top as the earth's equator, it will appear that the angle of intersection of the two planes does not change, although the place of intersection constantly does change, swinging around as the top swings.

To make the comparison altogether accurate, of course the table-planes and the top-planes should intersect at the center of the top itself. A top suspended in gimbal rings would more accurately illustrate the principle. But the ordinary spinning top is more familiar, and the principle of shifting point of intersection is illustrated just as accurately in one case as in the other.

Plate III: A Region of the Milky Way (Yerkes Observatory)
The relatively starless areas are called Dark Nebulae

We have only to imagine that the top, which in reality swings clear about in perhaps ten seconds, requires nearly 26,000 years for the process, and we have a clear picture of the genesis of the phenomenon of the precession of the equinoxes, which Hipparchus discovered.

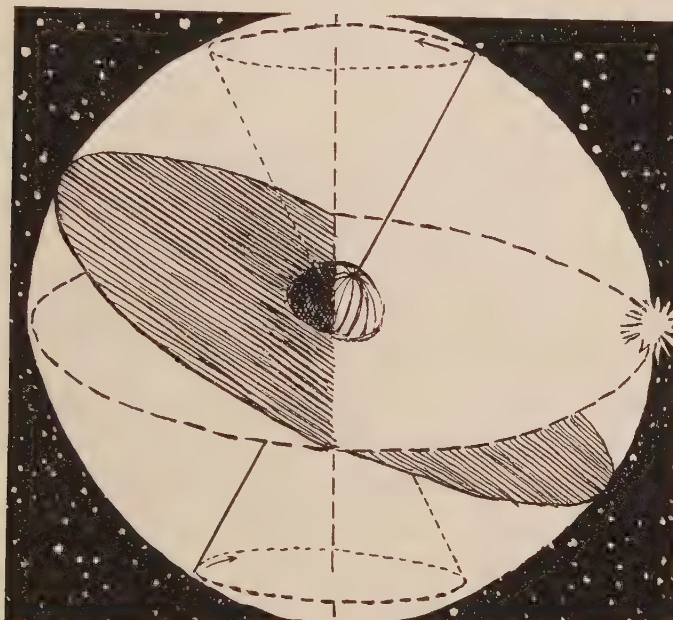

FIG. 15.—The Precession of the Equinoxes. Plane of Equator Shaded; Plane of Ecliptic Unshaded. Note the Big Dipper Pointing Out the Present Pole Star. At the Left is Vega, which will be the Pole Star About 13,000 Years from Now.

How Precession Was Discovered

Of course Hipparchus himself had no such mental picture of the process.

He supposed the earth to be stationary, and could only infer that the great vault of the firmament, in which what he supposed to be "fixed" stars were imbedded, revolved as a whole on an

axis about twenty-three degrees different from the axis of our globe. As to why such a revolution takes place he can have had no notion whatsoever. But for the matter of that, neither could he have any notion as to the reason for the observed movements of any other of the heavenly spheres that make up his system of epicycles.

His business was not to find explanations, but to observe phenomena, and to devise mechanical contrivances consistent with the motions observed.

Incidentally, the successors of Hipparchus were no better enlightened as to the cause of precession, even after it was known that the earth and not the heavens is responsible for the phenomenon, until Newton, with the aid of his law of gravitation, explained it as due to the disturbing tug of moon and sun on the earth's protuberant equatorial region.

Explanations aside, it was vastly to the credit of Hipparchus that he discovered a shift in star-positions which, in the term of one man's period of observation, is almost negligible. In thirty-five years, for example, the shift mounts to only about the apparent diameter of the moon.

It appears, however, that Hipparchus had access not alone to the records or star-charts of the old Babylonians, but also to Egyptian records that may have been even more helpful. Indeed it is more than probable that the phenomenon of precession, though unnamed, was familiar to Egyptian star-gazers of a much earlier period—in which case Hipparchus should be credited with re-discovery, rather than with first observation of precession.

On the Shoulders of Giants

This after all is but another case in which the observer of one generation builds on the work of his predecessors, and in which credit for discovery is given, and justly given, to the man

who makes tangible an idea that before him had been only vaguely adumbrated.

It was Newton himself who said: "If I have seen further than other men, it is because I have stood on the shoulders of giants."

Professor Simon Newcomb, commenting on this appraisal, and noting how truly a like comment could be made regarding Newton's great predecessors, carries the comparison back to Hipparchus, and concludes:

"If we seek the teachers and predecessors of Hipparchus, we find only the shadowy forms of Egyptian and Babylonian priests, whose names and writings are entirely lost."

But if thus we recognize that the discoveries of Hipparchus were not unaided, this detracts nothing from the fame of the greatest observing astronomer of antiquity. He was known further as the inventor of the planisphere, a device for the representation of the mechanism of the heavens. His computations of the properties of spheres led him also to what was virtually discovery of the method of trigonometry, giving him, therefore, a high position in the field of mathematics.

All in all, then, Hipparchus is a most heroic figure. His chart of more than one thousand stars would by itself give him secure position as the greatest observing astronomer of antiquity. His suggestion that longitude might be determined by observing the parallax of the moon in eclipse was a striking innovation, of basic importance for the geographer, even though the lack of a better timepiece than the water-clock made such observations only approximately successful.

Here was, in a word, an astronomer of almost universal genius. The verdict of posterity named him "father of systematic astronomy."

And as he was the greatest, so he was to be the last of the star-gazers of antiquity who made new contributions to the sum of astronomical knowledge—though he had one successor who was to achieve even wider fame as a cosmologist, as will appear in the succeeding chapter.

IV

PTOLEMY AND THE ALMAGEST

WE HAVE seen that the third century B. C. was a time when Alexandrian science was at its height, but that the second century produced also in Hipparchus at least one investigator of the very first rank; though, to be sure, Hipparchus can be called an Alexandrian only by courtesy.

In the ensuing generations the Greek capital at the mouth of the Nile continued to hold its place as the centre of scientific and philosophical thought. The kingdom of the Ptolemies still flourished with at least the outward appearances of its old-time glory, and a company of grammarians and commentators of no small merit could always be found in the service of the famous museum and library. But the whole aspect of world-history was rapidly changing. Greece, after her brief day of political supremacy, was sinking rapidly into desuetude, and the hard-headed Roman in the West was making himself master everywhere.

While Hipparchus of Rhodes was in his prime, Corinth, the last stronghold of the main-land of Greece, had fallen before the

prowess of the Roman, and the kingdom of the Ptolemies, though still nominally free, had begun to come within the sphere of Roman influence.

Just what share these political changes had in changing the aspect of Greek thought is debatable.

But there can be no question that, for one reason or another, the Alexandrian school as a creative centre went into a rapid decline at about the time of the Roman rise to world-power. There are some distinguished names, but, as a general rule, the spirit of the times is reminiscent rather than creative; the workers tend to collate the researches of their predecessors rather than to make new and original researches for themselves.

Eratosthenes, the inventive world-measurer, was succeeded by Strabo, the industrious collator of facts; Aristarchus and Hipparchus, the originators of new astronomical methods, were succeeded by Ptolemy, the perfector of their methods and the systematizer of their knowledge.

Ptolemy was a Greek and an Alexandrian. It does not appear that he was related to the aforetime royal family. His antecedents, indeed, are quite unknown.

Even the exact dates of Ptolemy's life are doubtful, but his recorded observations extend to the year 151 A. D.

He was a working astronomer, and he made at least one original discovery of some significance—namely, the observation of a hitherto unrecorded irregularity of the moon's motion, which came to be spoken of as the moon's evection. This consists of periodical aberrations from the moon's regular motion in its orbit, which, as we now know, are due to the gravitation pull of the sun, but which remained unexplained until the time of Newton.

Ptolemy also made original observations as to the motions of

the planets. He is, therefore, entitled to a respectable place as an observing astronomer. But his chief fame rests on his writings.

The Famous "Almagest"

His great works have to do with geography and astronomy. In the former field he makes an advance upon Strabo, citing the latitude of no fewer than five thousand places.

FIG. 16.—Ptolemy. (Redrawn from an old French print of doubtful authenticity.)

In the field of astronomy, his great service was to have made known to the world the labors of Hipparchus.

Ptolemy has been charged with appropriating the star-chart of his great predecessor without due credit. Undoubtedly he used that chart as the basis of his own. But it is almost certain that he had no thought of plagiarising. All along he is sedulous in his references to his predecessor.

Indeed, his work might almost be called an exposition of the astronomical doctrines of Hipparchus.

No one pretends that Ptolemy is to be compared with the Rhodesian observer as an original investigator, but as a popular expounder his superiority is evidenced in the fact that the writings of Ptolemy became practically the sole astronomical textbook of the Middle Ages both in the East and in the West, while the writings of Hipparchus were allowed to perish.

The most noted of all the writings of Ptolemy is the work which became famous under the Arabic name of *Almagest*. Origin of the Name

This word is curiously derived from the Greek title *E megiste syntaxis*, "the greatest synthesis" (or construction) a name given the book to distinguish it from a work on astrology in four books by the same author. For convenience of reference it came to be spoken of merely as *E megiste* from which the Arabs form the title *Tabair al Magisthi*, under which title the book was published in the year 827. From this is derived the word *Almagest*, by which Ptolemy's work continued to be titled among the Arabs, and subsequently among Europeans when the book again became known in the West.

Ptolemy's book, as has been said, is virtually an elaboration of the doctrines of Hipparchus. It assumes that the earth is the fixed centre of the solar system, and that the stars and planets revolve about it in twenty-four hours, the earth being, of course, spherical. It was not to be expected that Ptolemy should have adopted the heliocentric idea of Aristarchus. Yet it is much to be regretted that he failed to do so, since the deference which was accorded his authority throughout the Middle Ages would doubtless have been extended in some measure at least to this theory as well, had he championed it.

Contrariwise, his unqualified acceptance of the geocentric doctrine sufficed to place that doctrine beyond the range of challenge.

Scope of the "Almagest"

The Almagest treats of all manner of astronomical problems, but the feature of it which gained it widest celebrity was perhaps that which has to do with eccentrics and epicycles.

This theory was, of course, but an elaboration of the ideas of Hipparchus; but, owing to the celebrity of the expositor, it has come to be spoken of as the theory of Ptolemy. We have sufficiently detailed the theory in speaking of Hipparchus. It should be explained, however, that, with both Hipparchus and Ptolemy, the theory of epicycles would appear to have been held rather as a working hypothesis than as a certainty, so far as the actuality of the minor spheres or epicycles is concerned.

That is to say, these astronomers probably did not conceive either the epicycles or the greater spheres as constituting actual solid substances.

Subsequent generations, however, put this interpretation upon the theory, conceiving the various spheres as actual crystalline bodies.

It is difficult to imagine just how the various epicycles were supposed to revolve without interfering with the major spheres, but perhaps this is no greater difficulty than is presented by the alleged properties of the ether, which physicists of to-day accept as at least a working hypothesis.

We shall see later how firmly the conception of concentric crystalline spheres was held to, and that no real challenge was ever given that theory until the discovery was made that comets have an orbit that must necessarily intersect the spheres of the various planets.

Ptolemy's Geography and Columbus

Ptolemy's system of geography in eight books, founded on that of Marinus of Tyre, was scarcely less celebrated throughout the Middle Ages than the *Almagest*.

None of Ptolemy's original manuscripts has come down to us, but there is an alleged fifth-century manuscript attributed to Agathodæmon of Alexandria which has peculiar interest because it contains a series of twenty-seven elaborately colored maps that are supposed to be derived from maps drawn up by Ptolemy himself.

In these maps the sea is colored green, the mountains red or dark yellow, and the land white.

Ptolemy assumes that a degree at the equator is 500 stadia instead of 604 stadia in length. We are not informed as to the grounds on which this assumption was made, but it has been suggested that the error was at least partially instrumental in leading to one very curious result.

"Taking the parallel of Rhodes," says Donaldson, "he calculated the longitudes from the Fortunate Islands to Cattigara or the west coast of Borneo at 180°, conceiving this to be one-half the circumstance of the globe. The real distance is only 125° or 127°, so that his measurement is wrong by one-third of the whole, one-sixth for the error in the measurement of a degree and one-sixth for the errors in measuring the distance geometrically.

"These errors, owing to the authority attributed to the geography of Ptolemy in the Middle Ages, produced a consequence of the greatest importance. They really led to the discovery of America. For the design of Columbus to sail from the West of Europe to the east of Asia was founded on the supposition that the distance was less by one-third than it really was."

This view is perhaps a trifle fanciful, since there is nothing to

suggest that the courage of Columbus would have balked at the greater distance, and since the protests of the sailors, which nearly thwarted his efforts, were made long before the distance as estimated by Ptolemy had been covered.

Nevertheless it is interesting to recall that the geographical doctrines, upon which Columbus must chiefly have based his arguments, had been before the world in an authoritative form practically unheeded for more than twelve hundred years, awaiting a champion with courage to put them to the test.

As we take leave of Ptolemy, we are leaving the ancient world—though we shall hear of this last of the astronomers of antiquity again and again. Through him the ultimate thought of the Alexandrians was transmitted to posterity. No significant addition was to be made to the astronomical observations and doctrines it embalms for about thirteen centuries—incredible as that may seem.

Throughout that long period, the round, immovable earth as the centre of the universe, with the heavenly bodies revolving about it in a mesh of cycles and epicycles, was to be the unchallenged doctrine of astronomers—wherever astronomers existed.

V

ALBATEGNIUS—ALHAZEN—THE ARABS HOLD THE TORCH

Julius Caesar took back with him to Rome from the Egypt of Cleopatra the idea of reforming the calendar. His reform consisted essentially of the introduction of an extra day every

fourth year, to make up for the extra quarter-day each year that the earth requires for its complete circuit. This involved only an expedient that had been suggested upward of three centuries before by the Greek Eudoxus.

Through some official misunderstanding, the extra day was at first put in only every third year. After Caesar's death Augustus corrected this mistake. While he was about it, he decided to give his own month, August, an extra day, to make it equal to the month of his uncle Julius which preceded it. So he took the day from February.

With that record, ancient Rome appears for the first and last time in the story of astronomical progress. Ptolemy, though of the Roman period, was a Greek by birth and language. He had no immediate successors of his own race or any other.

In the centuries after him, the library at Alexandria was neglected, and its treasures, so far as they did not disappear altogether, were to be found not at Rome, but in Asia. Many of them were to be preserved through the curious channels of Arabic and Armenian translations.

And among the rest, the remarkable Synthesis of Ptolemy, the compendium of astronomical knowledge, which became famous as the *Almagest*. Oddly enough at a later day this work was brought by the Arabs into western Europe, and at the instance of Frederick II of Sicily translated out of their language into mediaeval Latin.

But in the meantime, the book had served as a source of knowledge and inspiration to a long line of Arabic astronomers, some of whom made respectable additions to observational knowledge of the stars and moon and planets, though no major discovery is recorded.

The Moslems did notable service in introducing from India the numerals that are now called Arabic. They also added to the astronomer's mathematical equipment by introducing into trigonometry the sine—the half-chord of the double arc—instead of the chord of the arc itself which the Greek astronomers had employed. This improvement was due to the famous Albategnius, whose work in other fields we shall examine in a moment.

Measuring the Earth

Another evidence of practicality was shown in the Arabian method of attempting to advance upon Eratosthenes' measurement of the earth.

Instead of trusting to the measurement of angles, the Arabs decided to measure directly a degree of the earth's surface—or rather two degrees. Selecting a level plain in Mesopotamia for the experiment, one party of the surveyors progressed northward, another party southward, from a given point to the distance of one degree of arc, as determined by astronomical observations.

The result found was fifty-six miles for the northern degree, and fifty-six and two-third miles for the southern.

Unfortunately, we do not know the precise length of the mile in question, and therefore cannot be assured as to the accuracy of the measurement. It is interesting to note, however, that the two degrees were found of unequal lengths, suggesting that the earth is not a perfect sphere—a suggestion the validity of which was not to be put to the test of conclusive measurements until about the close of the eighteenth century.

The Arab measurement was made in the time of Caliph Abdallah al-Mamun, the son of the famous Harun-al-Rashid.

Both father and son were famous for their interest in science. Harun-al-Rashid was, it will be recalled, the friend of Charlemagne. It is said that he sent that ruler, as a token of friendship,

a marvellous clock which let fall a metal ball to mark the hours. This mechanism, which is alleged to have excited great wonder in the West, furnishes yet another instance of Arabian practicality.

Perhaps the greatest of the Arabian astronomers was Mohammed ben Jabir Albategnius, or El-batani, who was born at Batan, in Mesopotamia, about the year 850 A. D., and died in 929.

Albategnius

Albategnius was a student of the Ptolemaic astronomy, but he was also a practical observer. He made the important discovery of the motion of the solar apogee.

That is to say, he found that the position of the sun among the stars, at the time of its greatest distance from the earth, was not what it had been in the time of Ptolemy.

The Greek astronomer placed the sun in longitude 65°, but Albategnius found it in longitude 82°, a distance too great to be accounted for by inaccuracy of measurement. The modern interpretation is that the line of apsides of the earth's orbit slowly revolves, but of course this inference could not well be drawn while the earth was regarded as the fixed centre of the universe.

In the eleventh century another Arabian discoverer, Arzachel, observing the sun to be less advanced than Albategnius had found it, inferred incorrectly that the sun had receded in the mean time. The modern explanation of this observation is that the measurement of Albategnius was somewhat in error, since we know that the sun's motion is steadily progressive. Arzachel, however, accepting the measurement of his predecessor, drew the false inference of an oscillatory motion of the stars, the idea of the motion of the solar system not being permissible.

Mistaken Ideas of "Trepidation"

This assumed phenomenon, which really has no existence, was

named the "trepidation of the fixed stars," and was for centuries accepted as an actual phenomenon. The observations of later generations have shown conclusively that the sun's shift of position is regularly progressive, hence that there is no "trepidation" of the stars.

If the Arabs were wrong as regards this supposed motion of the fixed stars, they appear to have made one correct new observation as to the inequality of motion of the moon.

Two inequalities of the motion of this body were already known. A third, called the moon's variation, was doubtfully discovered by an Arabian astronomer who lived at Cairo and observed at Bagdad in 975, and who bore the formidable name of Mohammed Aboul Wefaal-Bouzdjani.

The inequality of motion in question, by virtue of which the moon moves quickest when she is at new or full, and slowest at the first and third quarter, was rediscovered by Tycho Brahe six centuries later. The tradition that ascribes the original discovery to the Arabian is not quite fully authenticated.

Cordova a Centre of Influence

In the ninth and tenth centuries the Arabian city of Cordova, in Spain, was another important centre of scientific influence. There was a library of several hundred thousand volumes here, and a college where mathematics and astronomy were taught. Granada, Toledo, and Salamanca were also important centres, to which students flocked from western Europe.

It was the proximity of these Arabian centres that stimulated the scientific interests of Alfonso X. of Castile, at whose instance the celebrated Alfonsine tables were constructed.

A familiar story records that Alfonso, pondering the complications of the Ptolemaic cycles and epicycles, was led to remark

that, had he been consulted at the time of creation, he could have suggested a much better and simpler plan for the universe.

Some centuries were to elapse before Copernicus was to show that it was not the plan of the universe, but man's interpretation of it, that was at fault.

Another royal personage who came under Arabian influence was Frederick II (1194-1250 A. D.) of Sicily—the "Wonder of the World," as he was called by his contemporaries. The *Almagest* of Ptolemy was translated into Latin at his instance, being introduced to the Western world through this curious channel.

At this time it became quite usual for the Italian and Spanish scholars to understand Arabic although they were totally ignorant of Greek.

Alhazen Explains Twilight

In the field of physical science one of the most important of the Arabian scientists was Alhazen.

His work, published about the year 1100 A. D., had great celebrity throughout the mediaeval period.

The original investigations of Alhazen had to do largely with optics. He made particular studies of the eye itself, and the names given by him to various parts of the eye, as the vitreous humor, the cornea, and the retina, are still retained by anatomists.

It is known that Ptolemy had studied the refraction of light, and that he, in common with his immediate predecessors, was aware that atmospheric refraction affects the apparent position of stars near the horizon. Alhazen carried forward these studies, and was led through them to make the first recorded scientific estimate of the phenomena of twilight and of the height of the atmosphere.

The persistence of a glow in the atmosphere after the sun has disappeared beneath the horizon is so familiar a phenomenon

that the ancient philosophers seem not to have thought of it as requiring an explanation. Yet a moment's consideration makes it clear that, if light travels in straight lines and the rays of the sun were in no wise deflected, the complete darkness of night should instantly succeed to day when the sun passes below the horizon.

That this sudden change does not occur, Alhazen explained as due to the reflection of light by the earth's atmosphere.

Alhazen appears to have conceived the atmosphere as a sharply defined layer, and, assuming that twilight continues only so long as rays of the sun reflected from the outer surface of this layer can reach the spectator at any given point, he hit upon a means of measurement that seemed to solve the hitherto inscrutable problem as to the atmospheric depth.

Like the measurement of Aristarchus and Eratosthenes, this calculation of Alhazen is simple enough in theory.

Its defect consists largely in the difficulty of fixing its terms with precision, combined with the further fact that the rays of the sun, in taking the slanting course through the earth's atmosphere, are really deflected from a straight line by the constantly increasing density of the air near the earth's surface. Alhazen must have been aware of this, since it was known to the later Alexandrian astronomers, but he takes no account of it in the present measurement.

The diagram will make the method of Alhazen clear.

His important premises are two: first, the well recognized fact that, when light is reflected from any surface, the angle of incidence is equal to the angle of reflection; and, second, the much more doubtful observation that twilight continues until such time

as the sun, according to a simple calculation, is nineteen degrees below the horizon.

Referring to the diagram, let the inner circle represent the earth's surface, the outer circle the limits of the atmosphere, C being the earth's centre, and RR radii of the earth.

Then the observer at the point A will continue to receive the reflected rays of the sun until that body reaches the point S, which is, according to the hypothesis, nineteen degrees below the

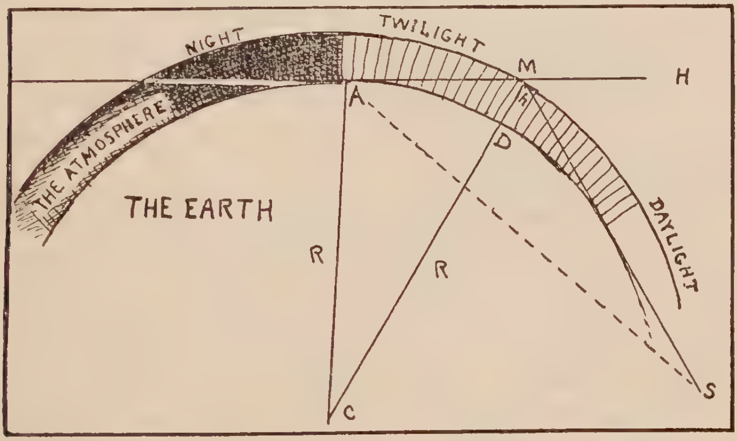

FIG. 17.—Alhazen's Explanation of Twilight. (For Explanation, See Text.)

horizon line of the observer at A. This horizon line, being represented by AH, and the sun's rays by SM, the angle HMS is an angle of nineteen degrees. The complementary angle SMA is, obviously, an angle of (180 — 19) one hundred and sixty-one degrees.

But since M is the reflecting surface and the angle of incidence equals the angle of reflection, the angle AMC is an angle of one-half of one hundred and sixty-one degrees, or eighty degrees and thirty minutes.

Now this angle AMC, being known, the right-angled triangle MAC is easily resolved, since the side AC of that triangle, being the radius of the earth, is a known dimension. Resolution of this triangle gives us the length of the hypotenuse MC, and the difference between this and the radius (AC), or CD, is obviously the height of the atmosphere (h), which was the measurement desired.

According to the calculation of Alhazen, this h, or the height of the atmosphere, represents from twenty to thirty miles. The modern computation extends this to about fifty miles. But considering the various ambiguities that necessarily attended the experiment, the result was a remarkably close approximation to later estimates of the truth.

The Arabian Cosmos

It is obvious, then, that the contribution of the Arabs to astronomy was by no means negligible. In particular, it is notable in contrast with the total inactivity of the people of Europe during all these centuries, in the fields of science in general, and of astronomy in particular. Yet, by and large, it is perhaps rather to be said that the Arabs held the torch of astronomical learning, than that they carried it greatly forward.

They handed the cosmos back to the western world—if the phrase be permitted—practically as they had received it from the Greeks, their Alexandrian predecessors.

The universe as they received it was the universe of Hipparchus and Ptolemy—a round, stationary earth at the centre, with planets, including the sun and moon, circling about in intricate systems of cycles and epicycles.

About the only difference was that the "spheres" of Hipparchus and Ptolemy were mostly regarded as imaginary contrivances, postulated for mathematical purposes and not envis-

aged as concrete mechanical structures. But the Arabs, harking back perhaps to their remote Oriental forebears, restored the concrete heavens of Egyptians and Babylonians—and extended the idea of a brazen or "molten glass" sphere of the starry firmament to include light glassy spheres for each of the numerous orbits of the planets.

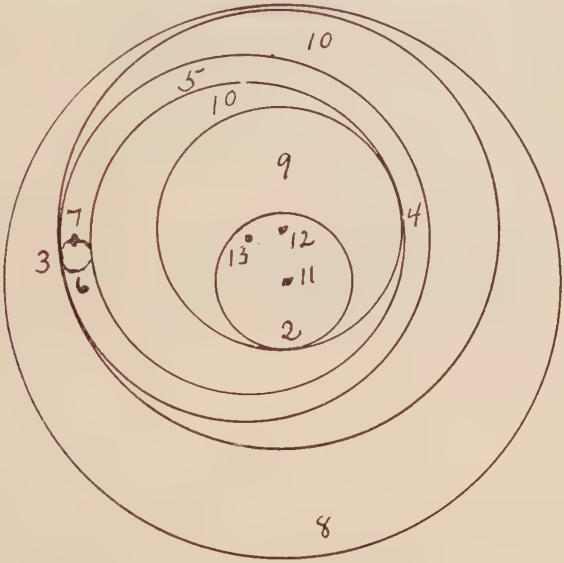

FIG. 18.—Arabian Conception of the Epicycles of Mercury. The Earth is at 11, but Points 12 and 13 are the Center of Some of the Eccentric Orbits; Mercury is at 7. (After Dreyer.)

It was this structure—this geocentric universe with its intricate system of star-studded and planet studded glassy spheres for heavens—that the Arabs re-introduced into Europe when the time came for Europe to revive its long-lost interest in matters astronomically cosmologic, in contradistinction to theologically cosmogonic.

And so, after a breathing space which we must imagine as

having lasted for more than 1200 years, while we were turning a score or so of pages, we shall be able to take up the story of astronomy in Europe, with the *Almagest* of Ptolemy for a text-book in the universities and for the only authoritative work in the library of the connoisseur—quite as if Ptolemy himself were still active down there in Alexandria, instead of having been in his grave for twice as many centuries as were compassed by the entire period of development of scientific astronomy in antiquity.

BOOK II

ASTRONOMY IN THE MEDIAEVAL PERIOD

"For the pillars of the earth are the Lord's and he hath set the world upon them."

—*Oriental Anthology.*

"He stretched out the north over the empty place, and hangeth the earth upon nothing."

—*Oriental Anthology.*

VI

THE CHRISTIAN WORLD—TWELVE CENTURIES OF PROGRESS (325-1543, A.D.)

FROM the Council of Nicaea, at which the Emperor Constantine made Europe safe for Athanasian Theocracy, to the time of Copernicus, whose great work, teaching that the earth is not the centre of the universe, was to remain under ban of the Council of the Inquisition until fifteen centuries after the Nicene victory, the record of astronomical progress in all Christendom may most charitably be expressed in these words:

BOOK III

SLOW DAWN OF THE NEW ERA

"Animals, which move, have limbs and muscles; the earth has no limbs or muscles, therefore it does not move. It is angels who make Saturn, Jupiter, the sun, etc., turn round. If the earth revolves, it must also have an angel in the centre to set it in motion; but only devils live there; it would therefore be a devil who would impart motion to the earth.

"The planets, the sun, the fixed stars, all belong to one species—namely, that of the stars. It seems, therefore, to be a grievous wrong to place the earth, which is a sink of impurity, among these heavenly bodies which are pure and divine things."

—*Scipio Chiaramonti.*

VII

COPERNICUS ENTHRONES THE SUN

THE first evidence of a revival of astronomical interest in the west was new activity in the field of exploration. In the Day of Columbus

Navigation is essentially an astronomical science. The navigator is and always has been a practical astronomer. In recent centuries he has made use of star-charts and astronomical tables provided for him by National Observatories, where more work is done in his interest than is done (or was until recently) in the interests of pure science in all other observatories put together.

Of course the 15th century navigator had a far less adequate astronomical equipment. Naturally he had no elaborate tables of ephemerides, and no telescopic sextant.

But he did have star-charts of a kind, notably that of Hipparchus, as preserved by Ptolemy, showing the thousand most conspicuous stars visible from the Northern Hemisphere. Then, too, he had the astrolabe and the cross-staff, the latter of which was the prototype of the quadrant and sextant of later times.

Lacking these instruments and a good practical knowledge of astronomy in its simpler aspects, any man would have been mad to put to sea on a voyage designed to take him out of sight of land. Even the compass, which also had come from Arabia, however indispensable it might be in cloudy weather, could by no means take the place of observations of sun and moon and stars, in charting a course at sea.

Use of the Cross-Staff

The cross-staff was an exceedingly simple instrument, consisting, as its name suggests, of a cross bar of wood sliding on a longer stick, or ruler, which, in practical use, was pointed toward the heavenly bodies under observation.

Squinting along the bar, as if sighting a gun, the user of the instrument, with his eye at the near end of the main stick, slid the cross-bar back and forth until its ends appeared to be in contact with the respective objects whose angular distance he desired to measure.

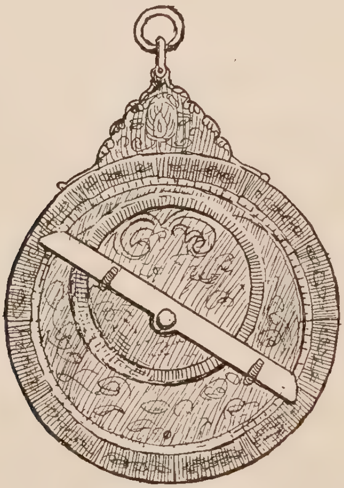

Fig. 19.—An Arabian Astrolabe for Measuring the Angular Elevation of Sun or Stars. (Note the Sights on the Rotating Lever. The Angle is Read Directly from the Circular Scale.)

Or the transverse bar might be held vertically, with one end seemingly touching the horizon, the other in contact with some star of known latitude, or with the sun or moon.

As the stars do not change their position, and as fairly accurate knowledge of the positions of sun and moon was available,

Columbus could not be in doubt as to his latitude, within a degree or two, at any time when the sky was unclouded.

The determining of longitude is a quite different matter, however, and this presented a problem that the navigator could not solve even approximately until some centuries after the time of

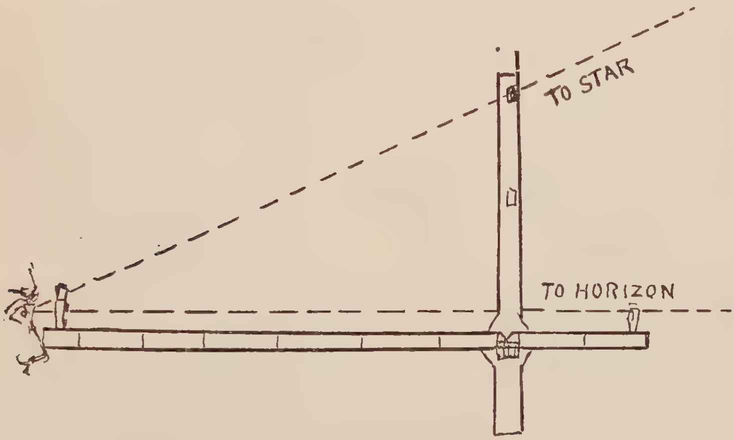

FIG. 20.—Cross Staff of Type Used by Columbus to Measure Elevation of the Sun or a Star.

Columbus, when the chronometer was invented. The clepsydra, or water-clock, which has served the ancient astronomers so well, could not be expected to operate satisfactorily on shipboard, and there is no record to suggest that this implement formed part of the equipment of Columbus.

To determine his longitude, the navigator was therefore obliged to depend on "dead-reckoning," or a rule-of-thumb estimate of the distance covered hour by hour. Considering the variability of wind and the uncertain influence of waves and ocean-currents, it cannot be supposed that Columbus was at any time certain of his longitudinal position within several hundred miles.

His task was simply to keep sailing westerly until he reached his destination; and to reverse the process on his return voyage. He knew about where he was as regards the distance from the equator; but his distance from Spain was conjectural both before and after he came to land at the outskirts of the western hemisphere.

The World Still Motionless

While the successful outcome of daring projects appeared to demonstrate the correctness of the ancient idea that the world is round, it had no bearing at all on the problem of the earth's motion—which, indeed, could perhaps hardly be called a problem, inasmuch as the conception of the earth's immobility, the centre of the universe, was not at this time challenged or considered matter for argument.

There was opportunity for possible difference of opinion as to whether the concentric spheres of Eudoxus, as championed by Aristotle, were more plausible than the epicycles of Ptolemy. But that the round world stood immovable at the centre of the universe, with the planetary bodies, including sun and moon, circling about it in successive spheres was matter of fully accepted knowledge—or challenged only by those who held that the earth is not round at all.

And the mobility of the earth, as a moment's reflection will show, was a question upon which the circumnavigation of the globe had no bearing whatsoever. The "naturalness" of the earth's position at the centre of the universe was accepted precisely as we moderns accept the "naturalness" of a body's falling toward the earth under domination of the utterly mysterious force we call gravitation.

Immediately following Columbus, da Gama sailed to India

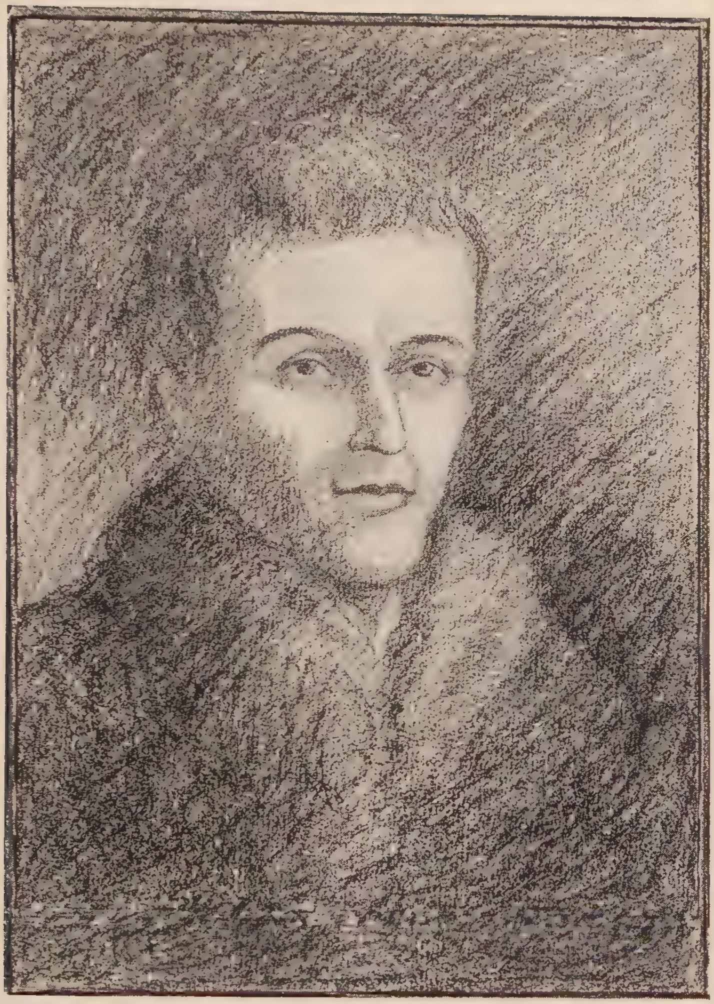

Plate IV: Nicholas Copernicus (1473-1543)
(Crayon composite, modified from the painting in possession of the Royal Society of England and other portraits)

around the southern point of Africa, and the expedition of Magellan circumnavigated the globe.

But these accomplishments may best be regarded as demonstrating the truth of the very ancient doctrine of the round world, which had come in with Pythagoras, and had been ardently championed by Aristotle and Hipparchus and Ptolemy, and which had in the course of centuries come to be regarded as matter of common knowledge, rather than as presaging a new astronomical era.

The round world had, indeed, been challenged by the ecclesiastical authorities of Europe in that long period which is characterized from one viewpoint as the age of Supreme Faith, and from another viewpoint as the Dark Age. But as Scholasticism gave way to Humanism through the insistent spread of traditional Greek doctrines which assumed the aspect of "new learning," the flat oriental world with its "waters above the firmament" had been effectively superseded by the round world and the universe of glassy spheres.

But this implied merely that the Egyptian and Babylonian cosmology of the second and third millenniums before Christ had been superseded by the Greek cosmology of the Alexandrian epoch.

It was no longer heresy to depart from the Oriental conception of a flat, four-cornered world; but the authorized cosmogony was still the cosmogony of the age of Moses and of Joshua and Isaiah.

The patrons of Columbus, and for aught we know Columbus himself, no more challenged the standing still of the sun and moon at the behest of Joshua, the turning back of the sundial on behalf of Hezekiah, than they challenged the rotundity of the central earth about which these minor planetary bodies revolved.

In a word, the Old Heavens and the Old Earth, whose ultimate passing Isaiah had prophesied, was still absolutely dominant. In its unquestioned acceptance, orthodox science and orthodox ecclesiastical dogma were at one.

To doubt that doctrine, in the age of Columbus, would perhaps hardly have been considered heresy, from the standpoint of either science or religion. It would have been considered rather as evidence of demoniacal possession—of literal madness.

All of which must be understood if we are clearly to comprehend the revolutionary character of the new conception of cosmology that was to be put forward on the semi-centennial of the completion of the first voyage of Columbus, by the iconoclast named Copernicus—inaugurator of the greatest revolution in thought mankind has ever known.

The Current Cosmology Summarized

The authoritative scientific attitude of the times is revealed in the work of Francesco Maurolico, of Messina, (1494-1575), whose *Cosmographia* was published, as it chanced, in the year 1543—the year made memorable by the publication of the work of Copernicus.

In this book Maurolico introduces a dialogue in which the teacher is made to say that human perversity has actually conceived the strange opinion that the earth might revolve on its axis.

That suggestion is repudiated with arguments altogether mediaeval in character.

An explication of the epicyclic system of Ptolemy is ornamented with metaphysical explanations of the reasons for the location and movements of the various planets—such as that Venus inclines more to the north and therefore has more dignity and must be above Mercury, while the latter in its motions resembles the moon and must therefore be next it.

Meantime there were not a few writers who reverted to the still more ancient doctrine of Eudoxus, substituting eccentric spheres for the deferents and epicycles of the later Greek system.

To two of these Dreyer refers when, in his concluding summary of the story of alleged precursors of Copernicus, he says:

"While in Italy, at the centre of civilization, Fracastoro and Amici were vainly endeavoring to put life into a mummy, while Calcagnini, in a most self-satisfied manner, was pretending that some motion of the earth, without its leaving the centre of the world, could solve every riddle presented by the stars, and while Maurolico was proving to the meanest intelligence that the earth could not possibly have any motion, a quiet student at the shore of the Baltic, on the very outskirts of civilization, was preparing to kindle the light which was to illuminate the universe and show to astonished humanity the earth moving through space."

The Coming of Copernicus

The "quiet student at the shore of the Baltic" was Niklas Koppernigk, famous in after time as Copernicus.

If a man's place among his fellows is to be judged by his ultimate influence in forwarding progress toward a comprehensive understanding of man's relation to the universe, the name of Copernicus is perhaps the greatest name in all human history.

For in the pronouncement of Copernicus, there was inherent the most supreme revolution in thought—the most cataclysmic reversal of attitude of mind—of which there is record.

From the hour when the "quiet student" enthroned the sun as the centre of the stellar system, dethroning the world, man's habitat, from the position of authority, man potentially ceased to be in his own estimate the supreme achievement of creation.

And the entire galaxies of anthropomorphic gods of all the

hierarchies tottered, preparatory to an abysmal plunge into the realm of nothingness.

From that hour the coils of ecclesiasticism, which in every generation had ruthlessly cramped the spirit of man, were potentially unloosed.

Oriental dogma, which had checked the advance of European civilization, plunging the world into a thousand years of darkness, was from that hour doomed.

A new era dawned for humanity.

It is true that several centuries were to elapse before the ghost of the old Oriental ogre could be laid. But that is only to say that evolution, not revolution, is the law of progress.

In speaking thus we are of course viewing Copernicus through the eyes of posterity. Let us go back now in imagination and endeavor to envisage him in the midst of his contemporaries, there at the beginning of the sixteenth century.

The Man Copernicus

He was born, we know, on February 19th, 1473, in the city of Thorn on the Vistula.

Curiously enough we know little about his ancestry; only that his father emigrated from Cracow to Thorn previous to 1458, and was a merchant of some social standing.

The city of Thorn lies in a province of that border territory which was then under the control of Poland, but which subsequently became a part of Prussia.

It is claimed that the aspects of the city were essentially German, and it is admitted that the mother of Copernicus belonged to that race. The nationality of the father is more in doubt, but it is urged that Copernicus used German as his mother-tongue.

His great work was, of course, written in Latin, according to

the custom of the time; but it is said that, when not employing that language, he always wrote in German.

The disputed nationality of Copernicus strongly suggests that he came of a mixed racial lineage.

The acknowledged centres of civilization towards the close of the fifteenth century were Italy and Spain. Therefore the birthplace of Copernicus lay almost at the confines of civilization, reminding us of that earlier period when Greece was the centre of culture, but when the great Greek thinkers were born in Asia Minor and in Italy.

As a young man, Copernicus made his way to Vienna to study medicine, and subsequently he journeyed into Italy and remained there many years. About the year 1500 he held the chair of mathematics in a college at Rome.

Subsequently he returned to his native land and passed his remaining years there, dying at his home in Frauenburg, East Prussia, in the year 1543. He is often referred to as the Canon of Frauenburg. It is said also that he practiced medicine. But few details of his actual activities have been preserved. Few that knew him suspected that his doings held any interest for posterity.

Long Decades of Pondering

It would appear that Copernicus conceived the idea of the heliocentric system of the universe while he was a comparatively young man. In the introduction to his great work which he addressed to Pope Paul III. he states that he has pondered his system not merely nine years, in accordance with the maxim of Horace, but well into the fourth period of nine years.

Throughout a considerable portion of this period the great work of Copernicus was in manuscript. But it was not published until the year of his death.

The reasons for the delay are not very fully established. Copernicus undoubtedly taught his system throughout the later decades of his life. He himself tells us that he had even questioned whether it were not better for him to confine himself to such verbal teaching, following thus the example of the Pythagoreans.

Just as his life was drawing to a close, he decided to pursue the opposite course, and the first copy of his work is said to have been placed in his hands as he lay on his deathbed.

The violent opposition which the new system met from ecclesiastical sources led subsequent commentators to suppose that Copernicus had delayed publication of his work through fear of the church authorities. There seems, however, to be no direct evidence for this opinion.

It has been thought significant that Copernicus addressed his work to the pope.

It is, of course, quite conceivable that the aged astronomer might wish by this means to demonstrate that he wrote in no spirit of hostility to the Church. His address to the pope might have been considered as a desirable shield precisely because the author recognized that his work would excite ecclesiastical criticism.

Be that as it may, Copernicus was removed by death from the danger of attack, and it remained for his disciples of a later generation to run the gauntlet of criticism and suffer the charges of heresy.

The Great Work on the Revolution of the Earth

The work of Copernicus, published thus in the year 1543 at Nuremberg, bears the title *De Orbium Caelestium Revolutionibus*.

The broader outlines of the cosmological system which Copernicus put forward are now familiar to everyone.

In a word, he supposed the sun to be the centre of all the

planetary motions, the earth taking its place among the other planets, the list of which, as known at that time, comprised Mercury, Venus, the Earth, Mars, Jupiter, and Saturn.

The fixed stars were alleged to be stationary, and it was necessary to suppose that they are almost infinitely distant, inasmuch as they showed to the observers of that time no parallax; that is to say, they preserved the same apparent position when viewed from the opposite points of the earth's orbit.

But let Copernicus speak for himself regarding his system. His exposition is full of interest. First, an excerpt from the introduction just referred to, in which appeal is made directly to the pope:

"I can well believe, most holy father, that certain people, when they hear of my attributing motion to the earth in these books of mine, will at once declare that such an opinion ought to be rejected.

"Now my own theories do not please me so much as not to consider what others may judge of them. Accordingly, when I began to reflect upon what those persons who accept the stability of the earth, as confirmed by the opinion of many centuries, would say when I claimed that the earth moves, I hesitated for a long time as to whether I should publish that which I have written to demonstrate its motion, or whether it would not be better to follow the example of the Pythagoreans, who used to hand down the secrets of philosophy to their relatives and friends only in oral form.

"As I well considered all this, I was almost impelled to put the finished work wholly aside, through the scorn I had reason to anticipate on account of the newness and apparent contrariness to reason of my theory.

"My friends, however, dissuaded me from such a course and admonished me that I ought to publish my book, which had lain concealed in my possession not only nine years, but already into four times the ninth year. Not a few other distinguished and very learned men asked me to do the same thing, and told me that I ought not, on account of my anxiety, to delay any longer in consecrating my work to the general service of mathematicians. . . .

"In order, however, that both the learned and the unlearned may see that I fear no man's judgment, I wanted to dedicate these, my night labors, to your holiness, rather than to any one else, because you, even in this remote corner of the earth where I live, are held to be the greatest in dignity of station and in love for all sciences and for mathematics, so that you, through your position and judgment, can easily suppress the bites of slanderers, although the proverb says that there is no remedy against the bite of calumny."

Details of the Copernicus Thesis

In chapter X. of book I., "On the Order of the Spheres," occurs a detailed presentation of the system, here quoted in part:

"That which Martianus Capella, and a few other Latins, very well knew, appears to me extremely noteworthy. He believed that Venus and Mercury revolve about the sun as their centre and they cannot go farther away from it than the circles of their orbits permit, since they do not revolve about the earth like the other planets.

"According to this theory, then, Mercury's orbit should be included within that of Venus, which is more than twice as great, and would find room enough within it for its revolution.

"If, acting upon this supposition, we connect Saturn, Jupiter, and Mars with the same centre, keeping in mind the greater

extent of their orbits, which include the earth's sphere besides those of Mercury and Venus, we cannot fail to see the explanation of the regular order of their motions.

"He is certain that Saturn, Jupiter, and Mars are always nearest the earth when they rise in the evening—that is, when they appear over against the sun, or the earth stands between them and the sun—but that they are farthest from the earth when they set in the evening—that is, when we have the sun between them and the earth.

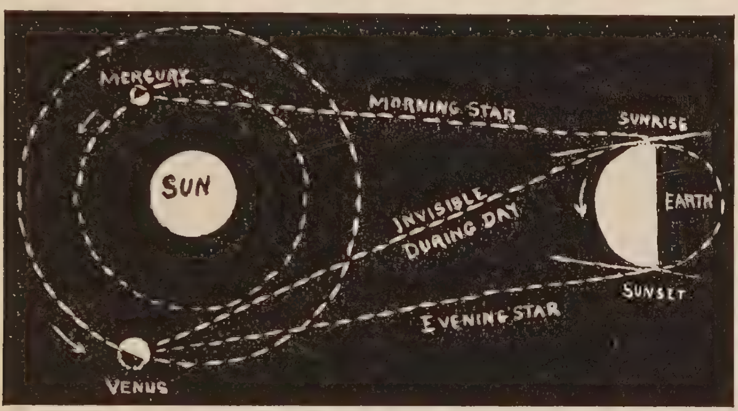

FIG. 21.—Correct Copernican Conception of Mercury and Venus.

"This proves sufficiently that their centre belongs to the sun and is the same about which the orbits of Venus and Mercury circle. Since, however, all have one centre, it is necessary for the space intervening between the orbits of Venus and Mars to include the earth with her accompanying moon and all that is beneath the moon; for the moon, which stands unquestionably nearest the earth, can in no way be separated from her, especially as there is sufficient room for the moon in the aforesaid space.

"Hence we do not hesitate to claim that the whole system,

which includes the moon with the earth for its centre, makes the round of that great circle between the planets, in yearly motion about the sun, and revolves about the centre of the universe, in which the sun rests motionless, and that all which looks like motion in the sun is explained by the motion of the earth.

"The extent of the universe, however, is so great that, whereas the distance of the earth from the sun is considerable in comparison with the size of the other planetary orbits, it disappears when compared with the sphere of the fixed stars. I hold this to be more easily comprehensible than when the mind is confused by an almost endless number of circles, which is necessarily the case with those who keep the earth in the middle of the universe.

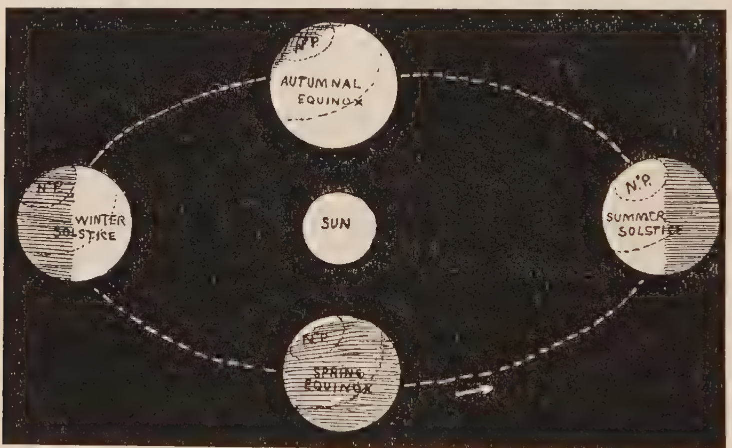

FIG. 22.—The Copernican Conception Explains the Seasons.

"Although this may appear incomprehensible and contrary to the opinion of many, I shall, if God wills, make it clearer than the sun, at least to those who are not ignorant of mathematics.

"The order of the spheres is as follows: The first and lightest of all the spheres is that of the fixed stars, which includes itself

and all others, and hence is motionless as the place in the universe to which the motion and position of all other stars is referred.

"Then follows the outermost planet, Saturn, which completes its revolution around the sun in thirty years; next comes Jupiter with a twelve years' revolution; then Mars, which completes its course in two years.

"The fourth one in order is the yearly revolution which includes the earth with the moon's orbit as an epicycle. In the fifth place is Venus with a revolution of nine months. The sixth place is taken by Mercury, which completes its course in eighty days.

"In the middle of all stands the sun, and who could wish to place the lamp of this most beautiful temple in another or better place.

"Thus, in fact, the sun, seated upon the royal throne, controls the family of the stars which circle around him. We find in their order a harmonious connection which cannot be found elsewhere.

"Here the attentive observer can see why the waxing and waning of Jupiter seems greater than with Saturn and smaller than with Mars, and again greater with Venus than with Mercury. Also, why Saturn, Jupiter, and Mars are nearer to the earth when they rise in the evening than when they disappear in the rays of the sun. More prominently, however, is it seen in the case of Mars, which when it appears in the heavens at night, seems to equal Jupiter in size, but soon afterwards is found among the stars of second magnitude.

"All of this results from the same cause—namely, from the earth's motion. The fact that nothing of this is to be seen in the case of the fixed stars is a proof of their immeasurable distance, which makes even the orbit of yearly motion or its counterpart invisible to us."

Copernicus Dies Opportunely

Copernicus was on his deathbed when the first copy of his book to come from the press was placed in his hands.

If still in possession of his faculties, he must have viewed the work with mingled emotions. For a preface had been introduced for which the author was in no way responsible, and the import of which cannot have been at all to his liking.

This new introductory matter—replacing an admirable foreword by Copernicus himself—had been interpolated, apparently, as a safeguard against the ecclesiastical authorities. It virtually begged the question as to the authenticity of the new scheme of the universe, speaking of the heliocentric doctrine as an hypothesis, and urging the permissibility of indulging in any speculation, even of dubious character, so long as it was understood to be speculation only.

The author of this Janus-facing introduction, which permanently marred the famous work, and for a long time was regarded by many critics as stultifying the character of Copernicus, perhaps acted with friendly intent. Of course it could not be known to the writer, who was connected with the press which issued the book, that Copernicus was about to pass from the scene, and therefore would be beyond the reach of any retribution which the Church might feel called on to exact.

More than likely, however, he was thinking of his own safety, and that of his associates of the printing office.

It was no light matter to be known as the publishers of a book which challenged in so dumbfounding a manner the most fundamental conceptions of the structure of the universe.

It is quite true that there is no rational association between Oriental theories of cosmology and the ethical questions that are supposedly the chief concern of religion. But, thanks to the atti-

tude of mind of the Church towards the ancient Hebrew literature, questions of cosmology had come to be regarded as fundamental parts of the theological structure.

The chance phrasing of an Oriental poet, which placed a moiety of the "divided waters" above the firmament, constituted for the entire mediaeval period a hurdle that the ecclesiastical mind could not get over.

For several hundred years this was an insuperable obstacle to the acceptance of the rotundity of the earth and the spheres of Ptolemy.

And now, just as a way was being found, or attempted, to harmonize the ancient poesy with such disturbing facts as the voyages of Columbus and Magellan and their fellows, there came this new iconoclast to make the horrifying suggestion that this round world is not only whirling on its axis at breakneck speed, but is actually swinging in a vast orbit about the sun.

The sun which, according to sacred tradition, had been manufactured in the sky as an appendage to the earth, as a candle and fire for man's benefit.

The sun which had stood still for hours on behalf of the hosts of Joshua, and had turned back in its course by ten degrees as a signal to Hezekiah.

Could the sun of Joshua and Hezekiah be a vast central body in the universe, about which the earth, man's habitat, flutters, like a moth about a candle?

That question was soon to be answered with authority; and it was probably fortunate for Copernicus that he was not alive to participate in the official demonstration of the falsity of his heretical doctrine.

Looking back, we date a new era from the year 1543, when

the book of Copernicus was published. But the contemporaries of Copernicus were few indeed who had the remotest suspicion of any change of the old order.

The old heavens and the old earth were not to be demolished with the flourish of a pen, nor within the lifetime of any single generation.

VIII

BRUNO THE PROTAGONIST

FIVE years after the death of Copernicus, there was born at Nola in Italy a child destined to become the earliest and most ardent of the protagonists of the new doctrine that the sun is the centre of the planetary system.

Giordano Bruno, the child in question, was born into a most remarkable epoch in human history.

We may place him at once in his contemporary environment if we recall that he was junior by fifteen years to Elizabeth of England; senior by four years to Sir Walter Raleigh; by thirteen years to Francis Bacon, by sixteen years to William Shakespeare. At the time of his birth his great compatriot Michelangelo had attained the age of seventy-three, but was destined to live for yet another sixteen years.

Luther had died two years before; and Bruno was a lad of five when Calvin, then in his prime, sent that other iconoclast Michael Servetus, there in Geneva, to the orthodox bloodless

death which almost half a century later was to claim the protagonist of the new heavens and the new earth.

One need not be a believer in predestination to realize that Giordano Bruno was born to meet the fate that befell him. He was by nature a non-conformist—a born iconoclast.

It was not at all a question as to what his end must be, but only as to when it would come.

Why the young iconoclast entered the Dominican order at Naples at the age of fifteen, no one can say. But it seems even stranger that thirteen years were to elapse before he hurriedly left Italy to avoid the consequences of his avowed disbelief in the doctrines of transubstantiation and of the immaculate conception.

That he was already an ardent champion of the new cosmology of Copernicus, goes without saying.

Safe for the moment beyond the confines of Italy, Bruno made his way to Geneva. He had forgotten, or perhaps had never heard, about Servetus, and he knew Switzerland by hearsay as the centre of one branch of the protesting priesthood, that had declared their emancipation from the autocracy of Rome.

Bruno at Geneva

There, surely, he would be free to speak his mind.

But sad disillusionment awaited him.

Calvinism, he found, was only the name for another type of autocracy. There was no greater receptiveness in Geneva than in Rome to the idea that the words of the Hebrew chronicler were fabulous. When Bruno talked about new scientific truths in opposition to tradition, he was reminded of that other champion of the new order who had come to Geneva hopefully twenty-six years before—and who had not departed in the flesh.

One can imagine Bruno making his way to the public square where Servetus had suffered, and brooding there in silence—the gruesome scene reenacted before the eyes of his imagination.

He had heard now, perhaps, that one of the unpardonable offences of Servetus had been that in his edition of Ptolemy's *Geography*, Judea had been thoughtlessly referred to as a land not "flowing in milk and honey," but in the main meagre, barren, and inhospitable. Such language, Calvin had declared "necessarily inculpated Moses, and grievously outraged the Holy Spirit."

Mild heresy that, compared to the suggestion that the earth is not the centre of the universe.

Yet Servetus had gone to the stake.

Calvin himself had wished to save Servetus from the faggots, he had been told—feeling that the headman's axe would exact an adequate penalty.

But the Protestant authorities, it appeared, had taken the same view of such matters that was traditional with the leaders of the church they had abandoned.

Blood must not be shed: the stake was the better alternative.

We may suppose that Bruno found little comfort in the contemplation of that alternative. He stood not on the order of his going, but departed from Geneva, and made his way to Paris. In that centre of learning he must surely find a receptive audience.

And he did find listeners, although officially denied the privilege of lecturing unless he would recant his heresies.

For a time he managed to evade those who would silence him; then he left Paris in turn and crossed the channel to England.

In the London of Elizabeth and Shakespeare and Bacon, he found that he needed the protection of the French ambassador.

Then at Oxford, at the famous university, he thought to find confrères of kindred spirit. Bruno at Oxford

Forty years had now elapsed since the revolutionary work of Copernicus was published. Surely at Oxford one must find champions of the heliocentric doctrine.

And what Bruno did find at Oxford was that the old cosmology of Aristotle, which was five hundred years out of date in the time of Ptolemy, was the authorized astronomical teaching.

Indeed, it was not merely that the old doctrines were still in vogue; there was a rule in force according to which any teacher who departed from whatsoever tenet of Aristotle, was fined five shillings—a not inconsiderable sum at that period—for each and every such departure.

Here, indeed, was the very stronghold of conservatism and bigotry.

The only scientific doctrines permitted to be taught were the doctrines of a man who had been dead for upward of eighteen hundred years! A more recent authority, to be sure, than Moses and Isaiah, one who had taught that the world is round, quite as Magellan had proved it to be. But one who had also taught just as explicitly that the earth is the centre of the universe; one who had refused to accept the doctrine of a rotating earth, let alone an earth that swings in a vast orbit through space.

What would Aristotle have said to this mad man Copernicus?

The question answers itself. So grotesque and impious a doctrine may not be even referred to in the temple of learning where the voice of the Stagirite pronounces the final word.

And so Bruno the protagonist again took up his journey, and next we learn of him at the University of Wittemberg, and then in other cities of Germany and France and Switzerland—ever

seeking an audience, ever being repulsed; nowhere finding any considerable number of listeners who were not hostile to the revolutionary doctrine of Copernicus, and to the other heresies to which this born iconoclast must needs give utterance.

Yet though never received hospitably, he is everywhere permitted to depart in peace. The Protestant countries will have none of Copernicus, but they have a measure of tolerance toward his absurd teachings, if for no other reason than because they are regarded as heresy in Italy.

Finis in Italy

So Bruno leads a stormy petrel life, which is not actively jeopardized until he reaches his forty-fourth year.

Then he makes the vital mistake of returning to Italy. A patron there has assured him welcome.

A well-meaning patron, no doubt. One of the scattered band of enthusiasts who were receptive to the new ideas. But, by the same token, a man of small influence with the ecclesiastical powers that dominated Italy.

And so the iconoclast had not been long in the native land from which he had fled sixteen years before, before he found himself in the grip of the officers of the Inquisition—who lodged him forthwith in a Roman dungeon.

Almost eight years this restless spirit languished there, shut off from the audience of man, deprived of speech, incapable of fulfilling that innate behest which impelled him, despite every menace, to proclaim to the world the truth as he saw it.

Then came the inevitable tragic sequel—excommunication, the fateful last march to the Campo del Fiori—the field of flowers—not far from the Vatican; and final expiation, at the stake, without shedding of blood.

Thus Copernicus was proved wrong, and the wisdom of the Orientals was vindicated.

The year was sixteen hundred, *Anno Domini.*

Fifty-seven years had elapsed since Copernicus published his book, and opportunely died. Two human generations. Time enough, one might suppose, to find a hearing for a scientific doctrine which not only has the supreme merit of being true, but, in the view of later generations, would seem to have the further merit of obvious plausibility.

But two generations after all count for little against the accumulated prejudice of thousands of generations of men, that had known no doctrine but that of the geocentric universe.

More than fifty generations had come and gone since Aristarchus of Samos first put forward the true heliocentric doctrine of the heavens; and the beginning of the seventeenth century of the Christian era—the age of Elizabeth and Bacon and Shakespeare—found the antique doctrine of the immobile central earth and the whirligig heavens as firmly ensconced in the minds of men as it had been in the day of Alexander the Great and Demosthenes and Aristotle.

There was augury of a new era in the inspiration of Copernicus; but the visible dawn of the new era was scheduled for a later century.

Meantime, as one reflects on the character of the arguments that stilled the voice of Bruno the protagonist, one recalls certain words of his Holiness Leo XIII, who, in a letter to Cardinal Parocchi in 1885, made in classical Latin this earnest pronouncement:

"The Catholic Church, which always has fostered whatsoever things are honest, whatsoever things are lovely, whatsoever things

are of good report, has always given to the study of the humanities the favor that it deserves, and in promoting it, has expended no slight portion of its best endeavor."

We may not doubt that the words are sincere.

At first blush they may seem incongruous, when one recalls the fate of a Bruno.

Yet after all perhaps they have small application to that misadventure. In the year 1600 the doctrine of the new cosmology doubtless did not seem honest, assuredly did not seem lovely, and by no manner of means was it a thing of good report.

These things it could become only with the lapse of time, and through the efforts of a succession of workers, whose investigations will successively claim our attention.

IX

TYCHO BRAHE THE GREAT OBSERVER

THE tenth chapter of the Book of Joshua contains one of the most stirring battle poems in all literature.

It tells how the five kings of the Amorites conspired against Israel, and encamped before Gibeon and made war against it. But the men of Gibeon sent in to Joshua, who came in haste from his camp at Giljol, and all the people of war with him, and all the mighty men of valour.

And the Lord said unto Joshua, fear them not; for I have delivered them into thine hands; there shall not a man of them

stand before thee. And the Lord discomfited the hosts of the kings, and slew them with great slaughter at Gibeon, casting down great stones from heaven upon them, and thus destroying even more than the children of Israel slew with the sword.

But there was danger that some might escape under cover of approaching darkness; wherefore Joshua made appeal to the Lord.

The Sun Stands Still

"Then spake Joshua to the Lord in the day when the Lord delivered up the Amorites before the children of Israel, and he said in the sight of Israel, Sun, stand thou still upon Gibeon; and thou, Moon, in the valley of Ajalon.

"And the sun stood still, and the moon stayed, until the people had avenged themselves upon their enemies. Is not this written in the book of Jasher? So the sun stood still in the midst of heaven, and hasted not to go down about a whole day.

"And there was no day like that before it or after it, that the Lord hearkened unto the voice of a man, for the Lord fought for Israel."

Little indeed could the court poet have forecast, when he inscribed those stirring words, how strange would be their influence over the minds of men of races yet unborn, far off to the west, two thousand years after Joshua, who alone of all men had been permitted to control the sun, went to his reward.

It was pardonable exaggeration that gave this unique distinction to Joshua.

For in reality there was another occasion when a yet more remarkable interference with the orderly progress of the celestial mechanism took place and found record.

You may read of it in Chapter 38 of the Prophet Isaiah. It concerns Hezekiah, King of Judah, who was at war with Sennacherib, King of Assyria.

The Sun Moves Backward

The Lord had already shown his favor by sending his angel to smite the camp of the Assyrians a hundred and four score and five thousand, so that when they arose early in the morning, behold they were all dead corpses. He was now to give yet more extraordinary evidence of his favor. Let the Prophet Isaiah himself tell the story:

"In those days was Hezekiah sick unto death. And Isaiah the prophet the son of Amoz came unto him, and said unto him, Thus saith the Lord, Set thine house in order: for thou shalt die, and not live.

"Then Hezekiah turned his face toward the wall, and prayed unto the Lord,

"And said, Remember now, O Lord, I beseech thee, how I have walked before thee in truth and with a perfect heart, and have done that which is good in thy sight. And Hezekiah wept sore.

"Then came the word of the Lord to Isaiah, saying,

"Go, and say to Hezekiah, Thus saith the Lord, the God of David thy father, I have heard thy prayer, I have seen thy tears: behold, I will add unto thy days fifteen years. And I will deliver thee and this city out of the hand of the king of Assyria: and I will defend this city. And this shall be a sign unto thee from the Lord, that the Lord will do this thing that he hath spoken:

"Behold, I will bring again the shadow of the degrees, which is gone down in the sun dial of Ahaz, ten degrees backward. So the sun returned ten degrees, by which degrees it was gone down."

Here, indeed, was poetic imagery of a high order. How could the poet be expected to know that in after times his words would be taken literally, and that on his testimony alone it would be believed by millions of people of remote ages that the sun had actually turned back ten degrees in its course?

Yet such is the power of words that this strange thing came to pass.

And well towards the close of the sixteenth century of a new era, the keenest-eyed searcher of the skies that perhaps ever lived would be found quoting the antique poems in proof that the sun does move round the earth as the ancient poets supposed it to move—and therefore cannot be a stationary body at the centre of the planetary system, as the modern iconoclast Copernicus had conceived it to be.

This keen-eyed searcher was named Tycho Brahe.

Accounted the greatest of observing astronomers, he denied the truth of the Copernican doctrine to the end of his life, and denied it explicitly on the ground of the authority of the Oriental poets whose words have just been quoted.

Which goes to show that the pen is mightier than the astrolabe.

I had almost said "telescope," but recalled just in time that this instrument was not invented till a few years after the death of the great Danish astronomer.

We shall see presently how the telescope, in the hands of a man who was born while Tycho Brahe was in his prime, was to reveal evidence which went far to shake the faith of at least the leaders of thought in the verisimilitude of the ancient poems. But our present concern is with the great observer who was obliged to depend on the unaided eye in his star-gazing, yet who made records that almost vie with those made in later days by users of the magnifying lenses.

As One Having Authority

Tycho Brahe, the Dane, was born at Knudstrup, in the year 1546—three years after the appearance of the revolutionary book of Copernicus.

He died at Prague, in Bohemia, in 1601—the year following the untimely death of Giordano Bruno.

Tycho's great work was done in a splendid observatory, which he built on the Island of Huene, under patronage of Frederick, king of Denmark.

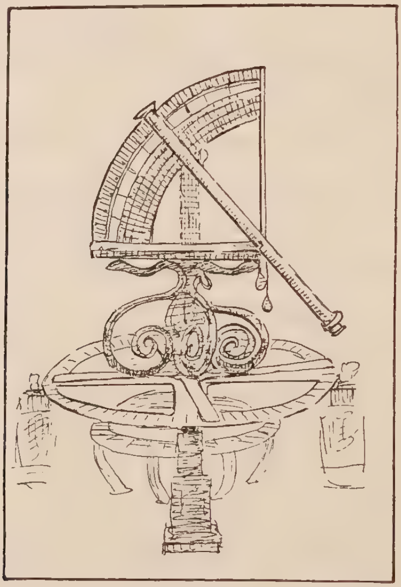

Fig. 23.—One of Tycho's Quadrants. (Redrawn from *Danneman's Geschichte der Naturwissenschaften.*)

Nothing comparable to this observatory had previously existed. Its equipment of astrolabes, armillary spheres, and allied apparatus, and his star-charts and celestial records were quite without example in his own age, and surpassed in subsequent ones solely because of the new instrument equipment developed after the invention of the telescope.

Throughout the latter part of the 16th century, Tycho was

the outstanding astronomical figure of the world. He spoke with the voice of full authority.

Against his verdicts, the words of such theorists as Bruno, and of the few minor astronomers who were inclined to accept the Copernican doctrine, were futile.

If the most accomplished observer of his age—generally reputed the greatest observer of any age—rejected the conception that the sun is the centre of the planetary system, it would be obvious presumption for any ordinary mortal to accept that doctrine.

Tycho's verdict as to the central thesis of Copernicus was unequivocal and emphatic.

All traditions placed the earth at the centre of the planetary system—at the centre of the universe. Even to challenge that view would be an impiety—a heresy. The earth, created as man's abiding place, is the great central and all-important body of the universe. That is the beginning and the end of the matter.

The earth is a sphere, fixed immovably at the centre of things. It neither rotates nor revolves. As to this, the arguments of Aristotle and Ptolemy, and of all other ancients of authority with a few negligible exceptions, are final and conclusive.

If the earth rotated, the wind would blow always as a terrific hurricane from the east; clouds would be driven incessantly westward, and an arrow shot straight up into the air would descend far to the west.

These are obvious truths, which hardly need repeating. Once for all, the world is at rest at the centre of the universe.

A Bizarre Compromise

Such was the verdict of Tycho, from which he never wavered. But when it came to consideration of the scheme of the remainder of the heavenly system, the great observer was led

presently to depart widely from the traditions of his ancient predecessors. For the more he studied the matter, the more clear it became to him that all the planets except the moon have the centres of their spheres of revolution in the sun, and not in the earth.

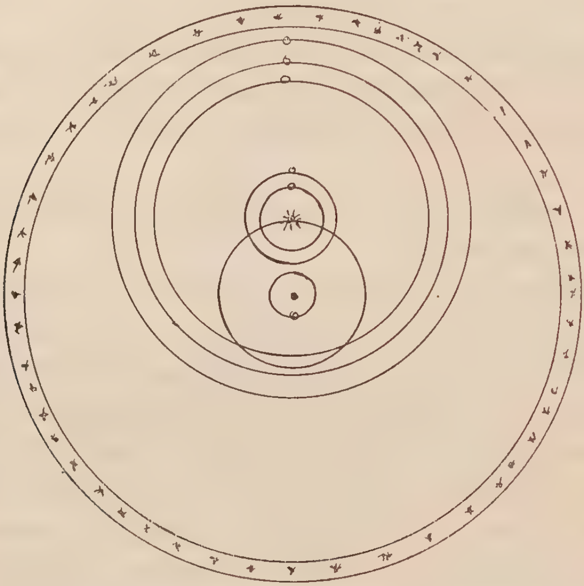

FIG. 24.—Tycho's System of the Universe. (Adapted from Dreyer's *History of the Planetary Systems.*) See Text for Explanation.

That the sun revolves about the earth, there can be no question. But it carries with it the five planets, Mercury, Venus, Mars, Jupiter, and Saturn, each revolving about the sun itself, while also being carried with the sun in the great circuit of the heavens about the terrestrial centre.

Here, then, was a curious compromise.

The strange plan became famous as the Tychonic system.

It was obviously a step in the direction of the heliocentric

system of Copernicus. Indeed, as regards the five planetary bodies, it was entirely in accord with the Copernican system. It was the sort of idea that might naturally have been conceived as an intermediate step between the old Ptolemaic system and the system of Copernicus.

Modern commentators, looking back, find it strange that it did not precede the Copernican system in time.

Had Tycho Brahe lived before Copernicus he would be regarded as having made an important contribution to cosmology, taking a long step forward, and arriving within striking distance of the true conception of the heliocentric planetary system.

As the case stands, Tycho's new system has only historical interest. His conception was reactionary, not progressive. It illustrates the power of tradition to mar the judgment of even the keenest mind.

Nevertheless, a Great Observer

But if Tycho thus fails as cosmologist, his achievements as an observing astronomer have excited the admiration of all subsequent generations.

One series of his observations, indeed, had an important bearing on the current conception of the planetary structure, in the direction of improved theory. This was his observation of a comet, which he examined with great care to determine if the visitor had parallax.

That is to say, he wished to determine whether the angle of vision of the comet varied when viewed in different parts of its orbit.

He found that the comet had no parallax.

This proved that the comet was very distant. Subsequently, however, the strange celestial visitor came much nearer to the sun. There could be no question that at one time it was more

distant than the planet Jupiter, at another time nearer than the planet Mars.

In other words, it had unquestionably passed through different spheres of the heavenly mechanism.

Now these spheres had come to be conceived as actual crystalline structures. This idea was not directly advocated, nor perhaps even implicitly, by Ptolemy, whose name was universally associated with the system of epicycles. But the Arabs had given tangibility to the idea. For them, the heavenly spheres were literal spheres of some transparent substance—solid spheres, in which the various planetary bodies were imbedded, as jewels might be imbedded in spheres of glass.

Tycho's observation of the comet demonstrated that this conception of the crystalline spheres could not be valid. Since the comet passed through the spheres, they are permeable.

In a word, imaginary spheres, not tangible actualities.

This constituted an advance upon the popular conceptions of recent generations. Yet, to conceive the planetary spheres as imaginary, was only to revert to the views of Hipparchus and Ptolemy and the other Greeks, who had first invented the heavenly mechanism. But no doubt Tycho's teaching had a share in preparing the world for the ultimate explanation, given a century later by Newton, of the control of the heavenly bodies by an intangible force of gravitation, rather than by any solid mechanism.

Advance in Lunar Theory

Tycho's elaborate studies of the moon enabled him to detect hitherto unknown inequalities of motion, constituting the first genuine advance in lunar theory since the time of Ptolemy.

Doubtful exception may be made of some observations of the

Arabian astronomers, for whom prior discovery of the so-called third inequality has been claimed.

New inequalities of motion of the various planets, in particular Mars, were also observed, calling for the introduction of new epicycles. Fortunately, however, the mechanism of the planetary orbits was conspicuously simplified by the admission of the sun as the centre of these orbits.

One of the great difficulties of the Ptolemaic system had resulted from the attempt to make all the planes of the planetary orbit pass through the centre of the earth, whereas in reality they pass through the centre of the sun.

Now that the truth was recognized, the mechanism of deferents and epicycles could be simplified.

Indeed, as regards the five planets, Tycho Brahe accepted the reasoning of Copernicus, and modified the scheme of epicycles accordingly.

When we reflect that there were contemporary astronomers who, rejecting the Tychonic system no less than the Copernican, had reverted to the pre-Ptolemaic system of Eudoxus and Aristotle, and were obliged to devise no fewer than seventy-seven spheres to account for the observed movements of the heavenly bodies, it will be obvious that the time was ripe for reform. Human credulity has its limits—though they are hard to find.

Tycho discovered independently a method, said to have been used by the Arabians, of determining the latitude of a place by two observations of a circumpolar star.

It is necessary only to determine the angle of elevation of the star on the meridian, and then its elevation twelve hours later when it again circles across the meridian. Half the sum of these angles gives the latitude of the place of observation.

At a later time the pole star itself would be used for this observation, with the aid of a small telescope to magnify the distance, only about one and a half degrees, of the star from the critical position.

A Miraculous New Star

The very brilliant new star which suddenly shone forth in the constellation of Cassiopea in the year 1572, was made the subject of special studies by Tycho, who proved that the star had no sensible parallax and consequently was far beyond the planetary regions.

Tycho records his astonishment on discovering a bright star at a place in the heavens where previously no star had been visible.

He was at first disposed to doubt the trustworthiness of his own eyes.

Only when he found that others also could see the star was he convinced.

Then he realized that he was witnessing a miracle—

"Even the greatest of all miracles that have occurred in the whole range of nature since the beginning of the world, or one certainly that is to be classed with those attested by Holy Oracles, the staying of the sun in its course in answer to the prayers of Joshua, and the darkening of the sun's face at the time of the Crucifixion."

He goes on to say that all philosophers agree, and the facts clearly prove, that in the ethereal region of the celestial world no change, in the way of generation or of corruption, takes place; but that the heavens and the celestial bodies in the heavens are without increase or diminution, and that they undergo no alteration, either in number or in size or in light or in any other respect.

Except only that Hipparchus is reported by Pliny to have noticed a star different from all others previously seen, one born in his own age.

Tycho then tells how he endeavored to tell whether the new star had parallax; the method being to observe the distance of the new star from a familiar star when on the meridian, and again when near the horizon.

He found the distance always the same—which is equivalent to saying that the star had no parallax.

It is, therefore, in an orbit so far above the lunar sphere that the semi-diameter of the earth has no sensible size in respect to it, the whole earth, when compared to it, being no more than a point. This has been found by the founders of science to be in the eighth sphere or not far from it, in the higher orbits of the three superior planets.

"Whence this star will be placed in the heavens themselves, either in the eighth orbit with the other fixed stars, or in the spheres which are immediately beneath.

"Therefore it is concluded that this star is not some kind of comet or fiery meteor, whether these be generated beneath the moon or above the moon, but that it is a star shining in the firmament itself—one that has never previously been seen before our time, since the beginning of the world."

Tycho's reasoning here is quite unassailable.

It is said that in later years he explained the phenomenon as due to the outbreak of a great celestial fire. In any event, it is hardly to be doubted that he regarded this "miracle" as a portent having significance for human observers. For the great Danish observer was still under the influence of the ancient tradition,

according to which the destinies of men are written in the stars.

He was, in other words, a firm believer in astrology.

The Last Great Astronomer-Astrologer

To say this is no disparagement, for in that age astrology ranked, in the minds of even the leaders of thought, as a veritable science.

The court astrologer took precedence of the accoucheur in royal confinement chambers, and the destinies of nations were sometimes in their hands, through their influence over kings and queens. Long after the age of Copernicus, astrology flourished.

But Tycho Brahe was perhaps the last astronomer of great prominence who was a conscientious practitioner of the art of divination.

In extenuation, let it be recalled that in England in this age of Elizabeth, and in the later reigns of William and Mary, judicial astrology was at its height.

After the great London fire, in 1666, a committee of the House of Commons publicly summoned the famous astrologer, Lilly, before Parliament, to report to them on his alleged prediction of the calamity that had befallen the city.

The astrologer, it may be added, denied that he had made such a prediction. He had been, he explained, "more interested in determining affairs of much more importance to the future welfare of the country."

This was, let it be recalled, a century and a quarter after the death of Copernicus, and at the beginning of the age of Newton.

We need not wonder, then, that Tycho Brahe, whose vision was crystal clear and his brain keen while his eyes were turned towards the stars, should have been unable to shake himself free from the incubus of this aspect of the ancient superstition—which after all was quite as logical a part of the Oriental in-

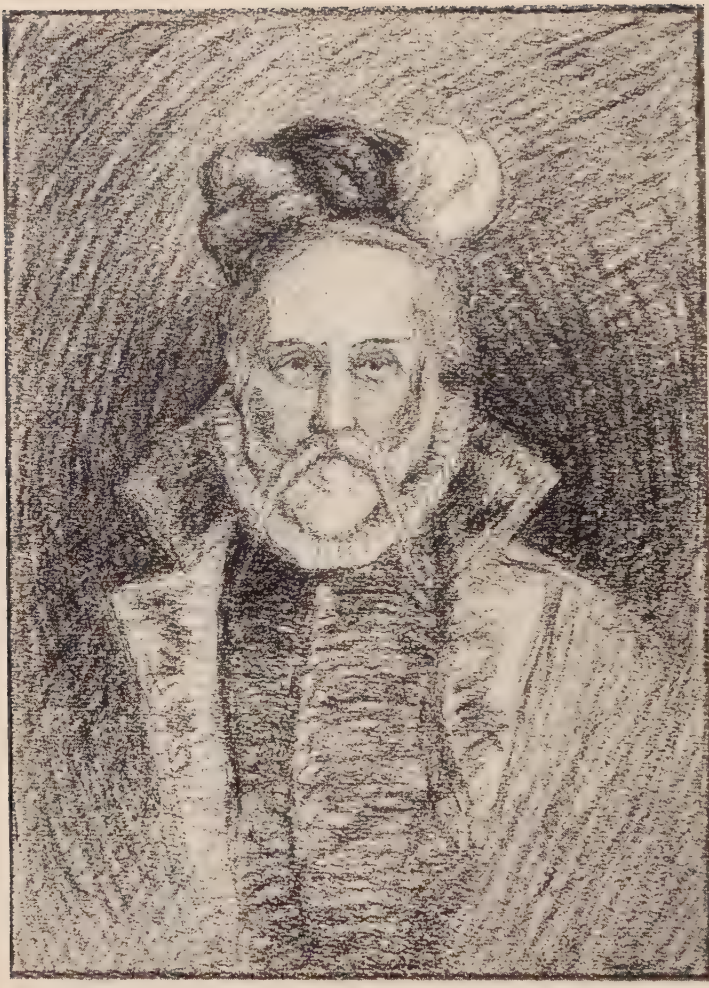

Plate V: Tycho Brahe (1546-1601)
(Crayon adaptation, from half-tone in Hutchinson's *Splendour of the Heavens*. Origin not traced)

heritance as the central thesis of a geocentric universe and a galaxy of anthropomorphic inhabitants of the celestial regions.

If it be true that Tycho Brahe, who died in 1601, was the last great astronomer who was also a sincere astrologer, it is also true that more than three hundred years after the death of the great observer there were probably more individuals in Christendom who believed in astrology than there were in his age.

And the anthropomorphic hosts of the celestial spheres are no less firmly ensconced in the minds of the multitudes than they were in the day when the most famous astronomer of his age could still believe that the earth is the centre of the universe.

X

KEPLER THE LAWGIVER

ENTER now a poet, a mystic, a metaphysical reasoner, who, in spite of these seemingly anomalous traits, is to take his place among the greatest practical discoverers of the astronomical world. By name, Johann Kepler. Birthplace, the little town of Weil, in Wurtemburg, Germany. One of the truly magnificent figures not merely of the scientific world, but of the human race.

Yet as a child this future "lawgiver" was weak and sickly, further enfeebled by a severe attack of smallpox.

It would seem paradoxical to assert that the parents of such a genius were mismated, but their home was not a happy one,

the mother being of a nervous temperament, which perhaps in some measure accounted for the genius of the child.

The father led the life of a soldier, and finally perished in the campaign against the Turks. Young Kepler's studies were directed with an eye to the ministry. After a preliminary training he attended the university at Tubingen, where he came under the influence of the celebrated Maestlin and became his life-long friend.

Curiously enough, it is recorded that at first Kepler had no taste for astronomy or for mathematics. But the doors of the ministry being presently barred to him, he turned with enthusiasm to the study of astronomy, being from the first an ardent advocate of the Copernican system.

His teacher, Maestlin, accepted the same doctrine, though he was obliged, for theological reasons, to teach the Ptolemaic system, as also to oppose the Gregorian reform of the calendar.

Reform of the Calendar

The Gregorian calendar, it should be explained, is so called because it was instituted by Pope Gregory XIII., who put it into effect in the year 1582, up to which time the so-called Julian calendar, as introduced by Julius Caesar, had been everywhere accepted in Christendom.

The Julian calendar was a great improvement on preceding ones, but still lacked something of perfection, inasmuch as its theoretical day differed appreciably from the actual day. In the course of fifteen hundred years, since the time of Caesar, this defect amounted to a discrepancy of about eleven days. Pope Gregory proposed to correct this by omitting ten days from the calendar, which was done in September, 1582.

To prevent similar inaccuracies in the future, the Gregorian calendar provided that once in four centuries the additional day

to make a leap-year should be omitted, the date selected for such omission being the last year of every fourth century.

Thus the years 1900 and 2300 A.D., would not be leap-years.

By this arrangement an approximate rectification of the calendar was effected, though even this does not make it absolutely exact.

FIG. 25.—The Constellation Cepheus. (Adapted from Bayer's *Uranometria,* of 1603.) Detail of a Star-chart of the Time of Kepler.

Such a rectification as this was obviously desirable, but there was really no necessity for the omission of the ten days from the calendar. The equinoctial day had shifted so that in the year 1582 it fell on the 10th of March and September. There was no reason why it should not have remained there. It would greatly have simplified the task of future historians had Gregory con-

tented himself with providing for the future stability of the calendar without making the needless shift in question.

We are so accustomed to think of the 21st of March and 21st of September as the natural periods of the equinox, that we are likely to forget that these are purely arbitrary dates for which the 10th might have been substituted without any inconvenience or inconsistency.

But the opposition to the new calendar, to which reference has been made, was not based on any such considerations as these.

It was due, largely at any rate, to the fact that Germany at this time was under sway of the Lutheran revolt against the papacy. So effective was the opposition that the Gregorian calendar did not come into vogue in Germany until the year 1699. It may be added that England, under stress of the same manner of prejudice, held out against the new reckoning until the year 1751, while Russia did not accept it till 1918.

As the Protestant leaders thus opposed the papal attitude in a matter of so practical a character as the calendar, it might perhaps have been expected that the Lutherans would have had a leaning towards the Copernican theory of the universe, since this theory was opposed by the papacy. Such, however, was not the case.

Luther himself pointed out with great strenuousness, as a final and demonstrative argument, the fact that Joshua commanded the sun and not the earth to stand still (again that regrettable image of the Hebrew poet!); and his followers were quite as intolerant towards the new teachings as were their ultramontane opponents.

Kepler himself was, at various times, to feel the restraint of

ecclesiastical opposition, though he was never subjected to direct persecution, as was his friend and contemporary, Galileo.

Kepler's First Book

At the very outset of Kepler's career there was, indeed, question as to the publication of a work he had written, because that work took for granted the truth of the Copernican doctrine.

This work appeared, however, in the year 1596. It bore the title *Mysterium Cosmographicum*, and it attempted to explain the positions of the various planetary bodies. Copernicus had devoted much time to observation of the planets with reference to measuring their distance, and his efforts had been attended with considerable success.

He did not, indeed, know the actual distance of the sun, and therefore was quite unable to fix the distance of any planet.

On the other hand, he determined the relative distance of all the planets then known, as measured in terms of the sun's distance, with remarkable accuracy.

With these measurements as a guide, Kepler was led to a very fanciful theory, according to which the orbits of the five principal planets sustain a peculiar relation to the five regular solids of geometry. His theory was this: "Around the orbit of the earth describe a dodecahedron—the circle comprising it will be that of Mars; around Mars describe a tetrahedron—the circle comprising it will be that of Jupiter; around Jupiter describe a cube —the circle comprising it will be that of Saturn; now within the earth's orbit inscribe an icosahedron—the inscribed circle will be that of Venus; in the orbit of Venus inscribe an octahedron—the circle inscribed will be that of Mercury."

Though this arrangement was a fanciful one, which no one would now recall had not the theorizer obtained subsequent fame on more substantial grounds, yet it evidenced a philosophical

spirit on the part of the astronomer which, misdirected as it was in this instance, promised well for the future.

Tycho Brahe, to whom a copy of the work was sent, had the acumen to recognize it as a work of genius.

FIG. 26.—The Constellation Hercules. (Adapted from Bayer's *Uranometria*, of 1603.) Detail of a Star Chart of the Time of Kepler.

He summoned the young astronomer to be his assistant at Prague, and no doubt the association thus begun was instrumental in determining the character of Kepler's future work. It was precisely the training in minute observation that could avail most for a mind which, like Kepler's, tended instinctively to the formulation of theories.

When Tycho Brahe died, in 1601, Kepler became his successor. In due time he secured access to all the unpublished observations

of his great predecessor, and these were of inestimable value to him in the progress of his own studies.

Kepler was not only an ardent worker and an enthusiastic theorizer, but he was an indefatigable writer, and it pleased him to take the public fully into his confidence, not merely as to his successes, but as to his failures. Thus his works elaborate false theories as well as true ones, and detail the observations through which the incorrect guesses were refuted by their originator.

Some of the mystic theories, indeed, were never relinquished.

Mystic Theories That Led to Laws

Thus the work which exposits the laws of planetary motion—laws that were to be foundation stones of the future science of celestial mechanics—calls the reader's attention to the fact that twenty-two years earlier Kepler had published the theory that the number of the planets or orbits about the sun was derived by the most wise Creator from the five solid figures about which Euclid so many centuries ago wrote the book which, since it is made up of a series of propositions, is called *Elementa*.

And Kepler adds:

"That there cannot be more regular bodies; that regular plain figures cannot unite into a solid in more than five ways, was made clear in the second book of the present work."

And he goes on to explain the ratios between the orbits of the planets and the basis of this imaginary relation—emerging miraculously with true laws of planetary motion which served at a single coup to demolish the entire structure of the antique mechanism of the heavens.

In the words of Lodge:

"After incredible labor, through innumerable wrong guesses, and six years of almost incessant calculation, he at length emerged in his 'two laws'—discoveries which swept away all epicycles,

deferents, equants, and other remnants of the Greek system, and ushered in the dawn of modern astronomy."

To which Shapley and Howarth add:

"His mystic temperament led to the happy inspiration of trying to get a relation connecting the size of orbits with times of

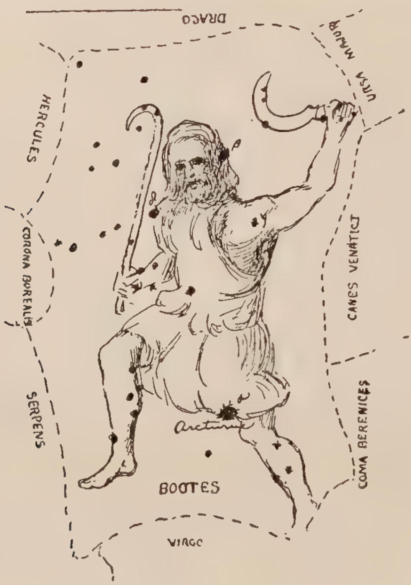

FIG. 27.—The Constellation Boötes. (Adopted from Bayer's *Uranometria*, of 1603.)

revolution and finally to the discovery of the 'third law,' which is given in 'Harmony of the World.'"

The Three Famous Laws

Here, concisely stated, are the interpretations of planetary motion in question, which have come to bear the name of Kepler's laws:

1. That the planetary orbits are not circular, but elliptical, the sun occupying one focus of the ellipses.

2. That the speed of planetary motion varies in different parts

of the orbit in such a way that an imaginary line drawn from the sun to the planet—that is to say, the radius vector of the planet's orbit—always sweeps the same area in a given time.

These two laws Kepler published as early as 1609. Many years more of patient investigation were required before he found out

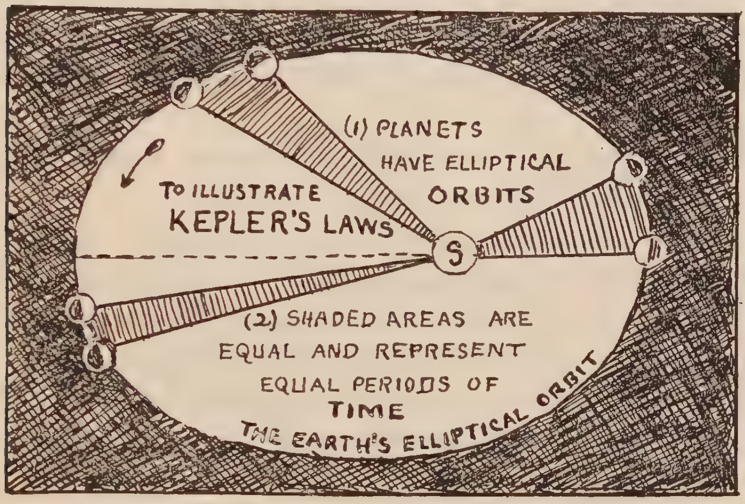

FIG. 28.—Diagram to Illustrate Kepler's First and Second Laws of Planetary Motion.

the secret of the relation between planetary distances and times of revolution which his third law expresses. In 1618, however, he was able to formulate this relation also, as follows:

3. The squares of the distance of the various planets from the sun are proportional to the cubes of their periods of revolution about the sun.

All these laws, it will be observed, take for granted the fact that the sun is the centre of the planetary orbits.

It must be understood, too, that the earth is constantly regarded, in accordance with the Copernican system, as being itself

a member of the planetary system, subject to precisely the same laws as the other planets.

Long familiarity has made these wonderful laws of Kepler seem such matters of course that it is difficult now to appreciate them at their full value.

Yet, as has been many times pointed out, it was the knowledge of these marvellously simple relations between the planetary orbits that laid the foundation of the Newtonian law of universal gravitation.

Contemporary judgment could not, of course, anticipate this culmination of a later generation.

What it could understand was that the first law of Kepler attacked one of the most time-honored of metaphysical conceptions—namely, the Aristotelian idea that the circle is the perfect figure, and hence that the planetary orbits must be circular.

Not even Copernicus had doubted the validity of this assumption. That Kepler dared dispute so firmly fixed a belief, and one that seemingly had so sound a philosophical basis, evidenced the iconoclastic nature of his genius. That he did not rest content until he had demonstrated the validity of his revolutionary assumption shows how truly this great theorizer made his hypotheses subservient to the most rigid inductions.

Sops to Cerberus

An inkling of the difficulties that confronted Kepler in announcing his discoveries is given in the "Introduction upon Mars."

"It must be confessed," Kepler says, "that there are very many who are devoted to Holiness, that dissent from the Judgment of Copernicus, fearing to give the Lye to Holy Ghost speaking in the scriptures if they should say, that the Earth moveth, and the sun stands still."

Kepler then urges that there is no real contradiction; that to speak of the sun as standing still may be a mere form of speech, just as Virgil speaks of the shore receding from the ship.

He gives assurance that the astronomer on whom God hath bestowed the gift of true vision, "though he seeth more clearly with the Eye Understanding, yet whatever he hath attained to, is both able and willing to extol his God above it."

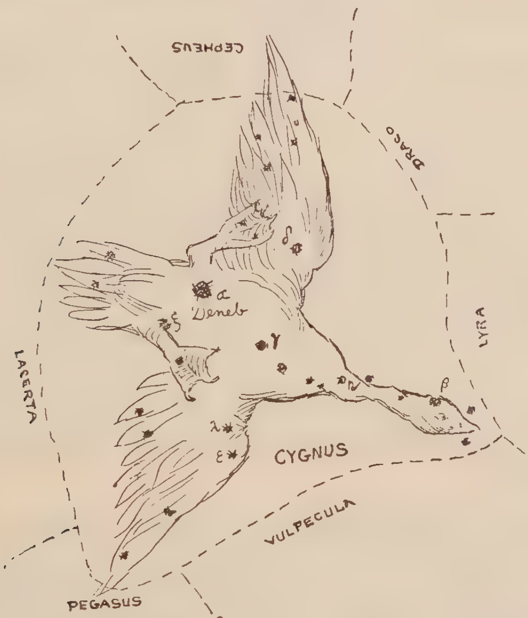

FIG. 29.—The Constellation Cygnus. (Adapted from Bayer's *Uranometria*, of 1603.) Note the Greek Letters First Used by Bayer to Designate Particular Stars.

Then, as touching the opinions of the Saints about these Natural Points, he urges that in theology the weight of Authority, but in philosophy the weight of Reason, is to be considered. Note, then, the conclusion:

"Therefore Sacred was *Lactantius,* who denied the Earth's

rotundity; Sacred was *Augustine,* who granted the Earth to be round, but denyed the *Antipodes,* Sacred is the Liturgy (Officium) of our Moderns, who admit the smallness of the Earth, but deny its Motion: But to me more sacred than all these is Truth, who with respect to the Doctors of the Church, do demonstrate from Philosophy that the Earth is both round, circumhabited by *Antipodes,* of a most contemptible smallness, and in a word, that it is ranked amongst the Planets."

It is to be noted that even in his later publications Kepler continues to refer to the prevailing skepticism about the new Copernican doctrine.

Thus in the treatise on Celestial Harmonies, telling of the goal ultimately achieved on the 15th of May, 1618 (in which the truth suddenly burst upon him, almost unbelievably, after seventeen years of labor), he states that among the mass of students the heliocentric idea is still unfamiliar, and the theory that the earth is one of the planets and moves among the stars about the sun, which is stationary, sounds to the most of them quite absurd.

It is to be noted also that in the same treatise, it is stated that among astronomers the fact is now well established that all the planets except the earth and moon revolve around the sun, implying acceptance of the Tychonic system for those that still reject the main thesis of the Copernican system; the alternative orbits being represented on the diagrammatic drawings that accompany the text. Kepler's veneration for the master observer whom he succeeded is so great that he speaks always with profound respect of any theory of Tycho, even though forced to disagree with it wholly or in part.

Wherein the Ellipse Differs

We moderns, who were taught Kepler's laws as fundamentals of celestial mechanics on our first introduction to astronomy, find it difficult to comprehend the revolutionary import of these seemingly simple conceptions.

There is no vast difference, as we conceive the matter, between a circle that is quite round and a slightly flat circle, which we term an ellipse.

But to the mediaeval mind, and to the scholastic mind of a later epoch, the difference seemed profound.

For them, the circle was the perfect figure, the ellipse an imperfect or distorted circle. To suggest that the celestial bodies pursue an elliptical, not a circular, course, is to suggest a fundamental defect in the mechanism of the heavens.

Such a suggestion amounts to blasphemy.

Hence the horror with which Kepler's first law, announcing the elliptical orbits of planets, was contemplated by a vast majority of his learned contemporaries.

On the other hand, for the open-minded investigator, the new conception came like an inspired mandate, bringing order out of chaos.

The thesis of Copernicus had, indeed, cleared away many of the cobwebs of the Ptolemaic system; but a certain number of epicycles still remained, and must remain so long as the planets were conceived to be moving in circular orbits. Instantly these epicycles disappeared when it was realized that the sun is not at the centre of any planetary orbit, but at one focus of an elliptical orbit.

The seeming loops in the orbits of planets, the varying speeds with which they move, were now explained.

There are more days from the vernal equinox to the autumnal

equinox than for the other half of the year, because the earth is then on the long leg of the ellipse, being farther from the sun at the summer solstice in June than at the winter solstice in December.

FIG. 30.—The Constellation Aquila, the Eagle. (Adapted from Bayer's *Uranometria*, of 1603.)

Every astronomer who could free his mind from the grip of the ancient superstitions must have viewed with profound relief the clarifying thesis which swept away the fifty-five or seventy-seven celestial spheres, and left a relatively simple mechanism, in which the six planets of which the earth is one move in their respective elliptical orbits about the sun, never faltering, never wavering, never turning on their tracks, but each moving at a rate predicated by Kepler's second law, and each governed also by the third law which, in Kepler's words, states that the periodic

times of any two planets are to each other exactly as the cubes of the square root of their median distances.

The explanation of the cause of these clearly revealed movements evaded the discoverer of the laws.

He was obliged even, as a concession to tradition, to suggest that each planet might be held in its course by the governing power of a guiding angel. But his laws had laid the foundation for the work of a great successor, who was to explain the movements of the planets on the profoundly simple principle of universal gravitation.

Before that greatest of mathematical astronomers came on the scene, however, a series of discoveries of another type was made by Kepler's contemporary, the famous Italian Galileo Galilei, to whose revelations we now turn.

XI

GALILEO AND HIS TELESCOPES

THIS great Italian champion of the Copernican doctrine was one of the most extraordinary scientific observers of any age. He was born at Pisa, on the 18th of February (old style), 1564.

The day of his birth is doubly memorable, since on the same day the greatest Italian of the preceding epoch, Michaelangelo, breathed his last.

Persons fond of symbolism have found in the coincidence a

forecast of the transit from the artistic to the scientific epoch of the later Renaissance.

Galileo came of an impoverished noble family. He was educated for the profession of medicine, but did not progress far before his natural proclivities directed him towards the physical sciences. Meeting with opposition in Pisa, he early accepted a call to the chair of natural philosophy in the University of Padua, and later in life he made his home at Florence.

The mechanical and physical discoveries of Galileo must not detain us. Our present concern is with his contribution to the Copernican theory.

Galileo himself records in a letter to Kepler that he became a convert to this theory at an early day. He was not enabled, however, to make any marked contribution to the subject, beyond the influence of his general teachings, until about the year 1610.

The brilliant contributions which he made were due largely to a single discovery—namely, that of the telescope.

Hitherto the astronomical observations had been made with the unaided eye. Glass lenses had been known since the thirteenth century, but, until now, no one had thought of their possible use as aids to distant vision. The question of priority of discovery has never been settled. It is admitted, however, that the chief honors belong to the opticians of the Netherlands.

The Discovery of the Telescope

As early as the year 1590 the Dutch optician Zacharias Jensen placed a concave and a convex lens respectively at the ends of a tube about eighteen inches long, and used this instrument for the purpose of magnifying small objects—producing, in short, a crude microscope.

Some years later, Johannes Lippershey, of whom not much is known except that he died in 1619, experimented with a some-

Plate VI: Johannes Kepler (1571-1630)
(Crayon interpretation of well-known portrait of untraced origin)

what similar combination of lenses, and made the startling observation that the weather-vane on a distant church-steeple seemed to be brought much nearer when viewed through the lens. The combination of lenses he employed is that still used in the construction of opera-glasses; the Germans still call such a combination a Dutch telescope.

FIG. 31.—Jan Lippershey, Inventor of the Telescope. (Redrawn from Bell's *The Telescope*, where it is credited to *Bull. de la Astron. de France.*)

Doubtless a large number of experimenters took the matter up and the fame of the new instrument spread rapidly abroad.

Galileo, down in Italy, heard rumors of this remarkable contrivance, through the use of which it was said "distant objects might be seen as clearly as those near at hand." He at once set to work to construct for himself a similar instrument, and his

efforts were so far successful that at first he "saw objects three times as near and nine times enlarged."

Continuing his efforts, he presently so improved his glass that objects were enlarged almost a thousand times and made to appear thirty times nearer than when seen with the naked eye.

The Mystery of the Milky Way is Solved

Naturally enough, Galileo turned this fascinating instrument towards the skies, and he was almost immediately rewarded by several startling discoveries. At the very outset, his magnifying-glass brought to view a vast number of stars that are invisible to the naked eye, and enabled the observer to reach the conclusion that the hazy light of the Milky Way is merely due to the aggregation of a vast number of tiny stars.

Turning his telescope towards the moon, Galileo found that body rough and earth-like in contour, its surface covered with mountains, whose height could be approximately measured through study of their shadows.

This was disquieting, because the current Aristotelian doctrine supposed the moon, in common with the planets, to be a perfectly spherical, smooth body.

The metaphysical idea of a perfect universe was challenged by this seemingly rough workmanship of the moon.

Thus far, however, there was nothing in the observations of Galileo to bear directly upon the Copernican theory. But when inspection was made of the planets the case was different. With the aid of his telescope, Galileo saw that Venus, for example, passes through phases precisely similar to those of the moon, due, of course, to the same cause.

Here then was demonstrative evidence that the planets are dark bodies reflecting the light of the sun, and an explanation was given of the fact, hitherto urged in opposition to the Coperni-

can theory, that the inferior planets do not seem many times brighter when nearer the earth than when in the most distant parts of their orbits; the explanation being of course, that when the planets are between the earth and the sun only a small portion of their illumined surfaces is visible from the earth.

Jupiter Has Moons, and the Sun Spots!

On inspecting the planet Jupiter, a still more striking revelation was made. Four tiny stars were observed to occupy an equatorial position near that planet, and were seen, when watched night after night, to be circling about the planet, precisely as the moon circles about the earth.

Here, obviously, was a miniature solar system—a tangible object-lesson in the Copernican theory. In honor of the ruling Florentine house of the period, Galileo named these moons of Jupiter, Medicean stars.

Turning attention to the sun itself, Galileo observed on the surface of that luminary a spot or blemish which was gradually modified in shape, suggesting that changes were taking place in the substance of the sun—changes obviously incompatible with the perfect condition demanded by the metaphysical theorists. But however disquieting for the conservative, the sun's spots served a most useful purpose in enabling Galileo to demonstrate that the sun itself revolves on its axis, since a given spot was seen to pass across the disk and after disappearing to reappear in due course. The period of rotation was found to be about twenty-four days.

It must be added that various observers disputed priority of discovery of the sun's spots with Galileo.

Unquestionably a sun-spot had been seen by earlier observers, and by them mistaken for the transit of an inferior planet. Kepler himself had made this mistake. Before the day of the tele-

scope, he had viewed the image of the sun as thrown on a screen in a camera-obscura, and had observed a spot on the disk which he interpreted as representing the planet Mercury, but which, as is now known, must have been a sun-spot, since the planetary disk is too small to have been revealed by this method.

FIG. 32.—Craters and Mountains on the Moon. (Redrawn from Mt. Wilson Photo.) Galileo's Telescope did not Reveal such Detail, but did Show that the Moon's Surface is Rough, thus Refuting the Aristotelian Conception of the Perfect Sphere.

Such observations as these, however interesting, cannot be claimed as discoveries of the sun-spots.

It is probable, however, that several discoverers (notably Johann Fabricius) made the telescopic observation of the spots, and recognized them as having to do with the sun's surface, almost simultaneously with Galileo. One of these claimants was a

Jesuit named Scheiner, and the jealousy of this man is said to have had a share in bringing about that persecution to which we must now refer.

There is no more famous incident in the history of science than the heresy trial through which Galileo was led to the nominal renunciation of his cherished doctrines. The Famous "Dialogue"

There is scarcely another incident that has been commented upon so variously. Each succeeding generation has put its own interpretation on it. The facts, however, have been but little questioned.

It appears that in the year 1616 the church became at last aroused to the implications of the heliocentric doctrine of the universe.

Apparently it seemed clear to the church authorities that the authors of the Bible believed the world to be immovably fixed at the centre of the universe. Such, indeed, would seem to be the natural inference from various familiar phrases of the text, and what we now know of the status of Oriental science in antiquity gives full warrant to this interpretation.

There is no reason to suppose that the conception of the subordinate place of the world in the solar system had ever so much as occurred, even as a vague speculation, to the authors of Genesis.

In common with their contemporaries, they believed the earth to be the all-important body in the universe, and the sun a luminary placed in the sky for the sole purpose of giving light to the earth.

There is nothing strange, nothing anomalous, in this view; it merely reflects the current notions of Oriental peoples in antiquity. What is strange and anomalous is the fact that the

Oriental dreamings thus expressed could have been supposed to represent the acme of scientific knowledge.

Yet such a hold had these writings taken upon the Western world that not even a Galileo dared contradict them openly; and when the church fathers gravely declared the heliocentric theory necessarily false, because contradictory to Scripture, there were probably few people in Christendom whose mental attitude would permit them justly to appreciate the humor of such a pronouncement.

And, indeed, if here and there a man might have risen to such an appreciation, there were abundant reasons for the repression of the impulse, for there was nothing humorous about the response with which the authorities of the time were wont to meet the expression of iconoclastic opinions.

The burning at the stake of Giordano Bruno, in the year 1600, was, for example, an object lesson well calculated to restrain the enthusiasm of other similarly minded teachers.

Doubtless it was such considerations that explained the relative silence of the champions of the Copernican theory, accounting for the otherwise inexplicable fact that about eighty years elapsed after the death of Copernicus himself before a single text-book expounded his theory.

The text-book which then appeared, under date of 1622, was written by the famous Kepler, who perhaps was shielded in a measure from the papal consequences of such hardihood by the fact of residence in a Protestant country.

Not that the Protestants of the time favored the heliocentric doctrine—we have already quoted Luther in an adverse sense—but of course it was characteristic of the Reformation temper to oppose any papal pronouncement, hence the ultramontane

declaration of 1616 may indirectly have aided the doctrine which it attacked, by making that doctrine less obnoxious to Lutheran eyes.

Be that as it may, the work of Kepler brought its author into no direct conflict with the authorities.

But the result was quite different when, in 1632, Galileo at last broke silence and gave the world, under cover of the form of dialogue, an elaborate exposition of the Copernican theory.

Galileo, it must be explained, had previously been warned to keep silent on the subject, hence his publication doubly offended the authorities. To be sure, he could reply that his dialogue introduced a champion of the Ptolemaic system to dispute with the upholder of the opposite view, and that, both views being presented with full array of argument, the reader was left to reach a verdict for himself, the author having nowhere pointedly expressed an opinion.

But such an argument, of course, was specious, for no one who read the dialogue could be in doubt as to the opinion of the author. Moreover, it was hinted that Simplicio, the character who upheld the Ptolemaic doctrine and who was everywhere worsted in the argument, was intended to represent the pope himself—a suggestion which probably did no good to Galileo's cause.

E Pur Si Muove

The work was widely circulated, and it was received with an interest which evidences a wide-spread undercurrent of belief in the Copernican doctrine.

Naturally enough, it attracted immediate attention from the church authorities.

Galileo was summoned to appear at Rome to defend his conduct. The philosopher, who was now in his seventieth year, pleaded age and infirmity. He had no desire for personal experi-

ence of the tribunal of the Inquisition. But the mandate was repeated, and Galileo went to Rome.

There, as every one knows, he disavowed any intention to oppose the teachings of Scripture, and formally renounced the heretical doctrine of the earth's motion.

According to a tale which so long passed current that every historian must still repeat it though no one now believes it authentic, Galileo qualified his renunciation by muttering to himself, *"E pur si muove"* (it does move, none the less), as he rose to his feet and retired from the presence of his persecutors.

The tale is one of those fictions which the dramatic sense of humanity is wont to impose upon history, but, like most such fictions, it expresses the spirit if not the letter of truth; for just as no one believes that Galileo's lips uttered the phrase, so no one doubts that the rebellious words were in his mind.

What he said aloud there, publicly, on his knees was this:

"I, Galileo, being in my seventieth year, being a prisoner and on my knees, and before your Eminence, having before my eyes the Holy Gospel, which I touch with my hands, abjure, curse, and detest the error and the heresy of the movement of the earth."

On his knees!

One of the great creative discoverers of all times on his knees before—the champions of an Oriental conception of cosmology which by the strange processes of the theocratic mind had come to be associated with fundamental problems of morality.

It is an edifying spectacle—amusing or otherwise according to the viewpoint. In the light of the sequel, it is not Galileo that needs our sympathy.

A few years later (1642) the heretic was dead, and buried without honor in unconsecrated ground.

When his friends sought permission to erect a monument over his remains, Pope Urban, refusing, stated simply and earnestly:

"It would be an evil example for the world if such honors were rendered to a man who had been brought before the Roman Inquisition for an opinion so false and erroneous; who had communicated it to many others, and who had given so great a scandal to Christendom."

Do the words sound quaint? Let us be logical. Let us admit that no one who believes the "Holy Gospel" (on which the heretic had his hand when he recanted) to be the word of God, can justly take issue with Pope Urban's verdict.

XII

HORROX—CASSINI—FLAMSTEED—EXPANDING THE SOLAR SYSTEM

EARLY in the afternoon of November 24, 1639, a young man, whose grave intelligent face and clerical costume did not altogether mask his boyishness, came hurriedly along a street of the little village of Toole, not far from the city of Preston, in Lancashire, England.

He glanced up at the sky eagerly, noted with a murmur of satisfaction that the sun was about to break through the clouds, and hurried on into his apartment.

A small room, with the blinds closed. There was darkness, almost as of night—except that a slender beam of light came through an aperture in a shutter and made a circular image, about six inches in diameter, on a sheet of paper adjusted vertically against a drawing-board at the opposite side of the room.

The boyish clergyman, his face now eagerly alert, closed the door carefully behind him, and went hurriedly across the room and stooped to scrutinize the circle of light, as if he hoped to find there some message of momentous import.

These were indeed troublous times in England. King Charles I. for the past ten years had governed without the Parliament, meeting the expenses of government by extraordinary measures of revenue, that had brought the people close to revolt. The year before, John Hampden had undergone a long-drawn-out trial for refusal to pay ship-money. The famous proposal to introduce the Episcopal Liturgy had provoked the Scots to the adoption of the Solemn League and Covenant, and now there was actual civil war, with the prospect that any day the armed forces might join in battle.

But the young clergyman, hurrying to the darkened room, eagerly scanning the disk of light, was not thinking of these things.

He was thinking only of an expected event, which, so he believed, was about to take place, not in England, but out in the depths of space, millions of miles away.

The spot of light which he scrutinized so eagerly, was the image of the sun, focused there through the small telescope which he had adjusted at the aperture in the shutter.

What he hoped to see was nothing more spectacular than a

dark, round spot, coming upon the disk of light at one side, and slowly creeping across the surface of the paper.

But he would know that spot, if it came, for the shadow of the planet Venus. Looking for the Transit of Venus

He would be elatedly conscious that he was witnessing something, the like of which had never been seen in all the world by human eyes, since time began.

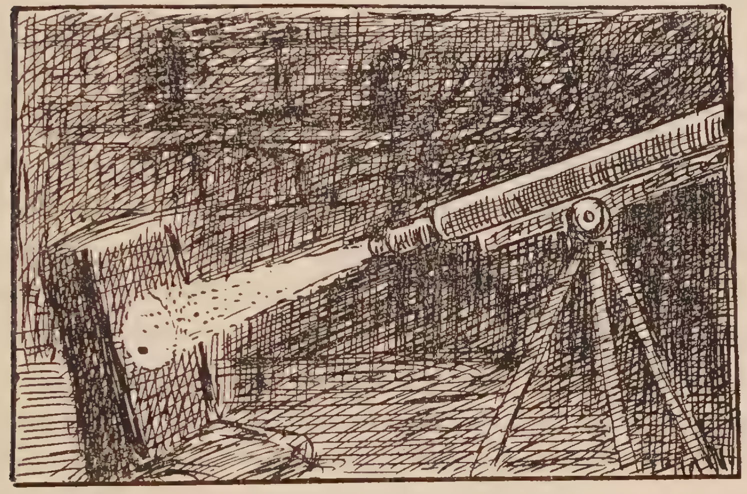

FIG. 33.—How Horrox Saw the Transit of Venus.

He, Jeremiah Horrox, a youth barely out of his 'teens, despite his ecclesiastical orders, was to witness—if Divine Providence permitted—a spectacle such as not even old Galileo, still alive down there in Italy (though forbidden to use his telescopes) had ever seen—nor Kepler, author of the Rudolphine Tables, with the aid of which this prospective transit of Venus had been calculated.

Needless to say, no earlier astronomer—neither Tycho, nor

Copernicus, nor old Hipparchus—could have dreamed of such a spectacle, living as they did in pre-telescopic days.

And within the thirty years since Galileo first turned a magnifying glass on the heavens, there had been no time when the planet Venus had passed directly between the earth and the sun, as the calculations of the young clergyman himself, fortified by the Rudolphine Tables, had clearly demonstrated.

But would the transit occur even now? Were the calculations on which the event was predicted accurate and dependable? The clergyman believed they were, yet he could not rid his mind of the thought that there might be, somewhere, a fallacy in the reckoning. But most of all he feared that the clouds might interfere so that the march of the little planet across the face of the sun, even though it occurred, would not be visible.

We have his own words for this. Writing after the event, he said:

"But lest a vain exultation should deceive me, and to prevent the chance of disappointment, I not only determined diligently to watch the important spectacle myself, but to exhort others whom I knew to be fond of astronomy to follow my example; in order that the testimony of several persons, if it should so happen, might the more effectively promote the attainment of truth; and because by observing in different places, our purpose would be less likely to be defeated by the accidental interposition of the clouds or any fortuitous impediment."

He goes on to say that his anxiety lest there be a clouded atmosphere was the greater because Jupiter and Mercury were in conjunction with the sun almost at the same time with Venus.

"This remarkable assemblage of the planets (as if they were desirous of beholding in common with ourselves, the wonders of the heavens, and adding to the splendor of the scene), seemed to forbode great severity of weather." The Planets and the Weather

Mercury, he adds, is especially to be feared, because its conjunction with the sun is invariably attended with storm and tempest.

"In this apprehension I coincide with the opinions of astrologers, because it is confirmed by experience; but in other respects I cannot help despising their more than puerile vanities."

Here, then, the young astronomer reveals that, despite his genius, he is not altogether free from credulous acceptance of tradition, or from hasty generalization, in ascribing such influence to the little interior planet over mundane affairs. Nor, it may be added, is he free by any means, from the influence of even less well-authenticated traditions of another type, since he tells us with fervor that the "clouds were dispelled as by Divine interposition," and records that he "was enabled, by Divine Providence to complete" effectually the observation of what, according to his own calculation, was a purely natural phenomenon.

As he gazed there at the disk for some minutes after he had returned to his apartment, he could not know whether his hopes and calculations were to be justified. He had not been very sure as to the exact hour, even the exact day, when the transit might occur—for the earlier tables with which he had begun his calculations had come to seem to him very erroneous, and even the Rudolphine Tables, fortified by his own observations, might lack something of precision.

True, he recorded afterward, he had relied on them implicitly,

and that they had forbade him to expect anything before three o'clock in the afternoon of this 24th day of November.

Nevertheless, to make quite sure, unwilling to depend entirely on his own opinion, lest by too much self-confidence he might endanger the observation, he had devoted as much time on the preceding day as he could spare to similar observations, and had steadily scanned the disk, moving the telescope with the sun, from sunrise to nine o'clock, and from a little before ten until noon, and at one in the afternoon—"being called away in the intervals by business of the highest importance, which for these ornamental pursuits, I could not with propriety neglect."

But during all this time he had seen nothing in the sun except a small and common spot, "consisting as it were of three points at a distance from the centre towards left," which he had noticed on the preceding day.

But this evidently had nothing to do with Venus.

Now, however, his expectations were to be justified.

Venus Appears

At about fifteen minutes past three, as he stood there in the darkened room with eyes intent on the image of the sun, which just covered the graduated circle, divided into degrees and fractions like a compass dial, which he had inscribed on the paper, he noted a slight indentation at the border of the disk, about 25 degrees below the equatorial line—and realized with elation that his prediction was on the point of being verified.

"I then beheld a most agreeable spectacle, the object of my sanguine wishes, a spot of unusual magnitude and of a perfectly circular shape, which had already fully entered upon the sun's disk on the left, so that the limbs of the Sun and Venus precisely coincided, forming an angle of contact. Not doubting that

this was really the shadow of the planet, I immediately applied myself sedulously to observe it."

What he observed was that the Venus-spot was very closely one-thirtieth of the size of the solar diameter.

He saw this shadow move partly across the solar disk for half an hour, and then the sun sank below the horizon. He had, however, completed all the observations that could possibly be made in so short a time, and he was able, subsequently, to make inferences from these observations that gave him a more correct notion as to the distance of the sun from the earth than anyone on the world had ever clearly entertained before.

Inspired Guessing

There was an element of inspired guessing in his estimate, for a single observation of a transit of Venus does not give data from which the sun's parallax can be accurately computed.

A second simultaneous observation from a different part of the earth's surface is necessary to supply such data.

The distance between the two points of observation serves as a base line for "triangulation" or "trigonometric" calculation of the planet's distance.

As young Horrox was probably the only man in the world who was considering the transit of Venus that day, there was obviously no such second observation available.

Nevertheless, it is recorded that the young clergyman, doubtless aided by astronomical observations of other types, within the two years of life that remained to him, was able to satisfy himself that the sun's parallax could not be greater than 14 seconds of arc.

This is only about five seconds more than the true parallax, as determined long afterwards—an amazing approximation to the truth, when it is recalled that the contemporaries and prede-

cessors of the youthful astronomer regarded something like 180 seconds as the sun's parallax, thus reckoning the sun's distance as less than one-twelfth of what young Horrox now computed.

To be known as the first man to predict and to observe a transit of Venus, would constitute a distinction giving a secure place in the history of astronomy. To have accomplished such a feat at the age of twenty years, is to have demonstrated an astounding precocity of genius.

But the young clergyman who accomplished this feat by no means paused with that. He made further demonstration of original genius of the highest order by a series of discoveries and creative estimates, any one of which by itself would have given distinction to the astronomer who made it, had it been the sole accomplishment of a lifetime.

Thus he was first to discover that the orbit of the moon is an ellipse, with the earth at one focus—a rare secret which even the "extreme sagacity and genius almost divine" of Kepler had missed, notwithstanding his recognition of the elliptical orbits of the planets. His skill as an observer is further attested by his discovery of the inequality in the mean motion of Jupiter and Saturn. His ingenuity of invention is evidenced by the devisement of "a beautiful experiment of the circular pendulum" for illustrating the action of a central force. He commenced a regular series of tidal observations, effected improvements in different astronomical tables, wrote opinions upon the nature and movement of comets, and recommended the adoption of decimal notation.

It has even been said that he had clearer intimations of the law of gravitation—though he died two years before Newton was born. As to that, it should be recalled, that a general conception

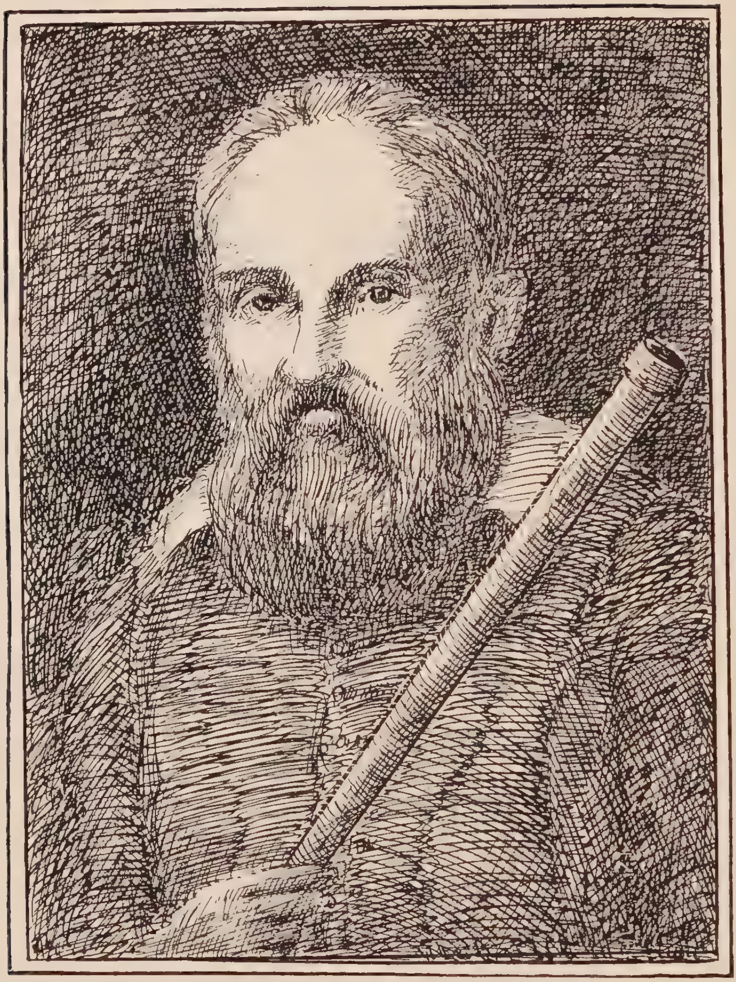

Plate VII: Galileo Galilei (1564-1642)
(Crow-quill adaptation, introducing one of the famous telescopes, based on an old engraving of untraced origin reproduced in Williams' *History of Science*)

of the probable truth of what came to be known as the law of Inverse Squares—the operation of a law of gravitational force decreasing as the square of the distance—was forecast by a number of Newton's contemporaries.

But, waiving this point, the amazing extent and variety of the original achievements of young Jeremiah Horrox, must give him secure place in the list of the world's astronomers of supreme original genius.

One finds it hard to avoid the futile speculation as to what might have been his aggregate achievements had he been spared to attain full maturity. If the promise—more than promise—of the formative years be considered a valid augury, it would seem that, but for his untimely demise, Jeremiah Horrox must have attained a plane of achievement not far below the supreme pinnacle where Isaac Newton, whose contemporary he should have been had fate been less unkind, now stands alone.

The Solar System Magnified

Fully to appreciate how far in advance of his time the young clergyman was, it must be noted that not until the thirtieth year after his death did any one else attain his quality of vision as to the true distance of the earth from the sun—that is to say, as to the essential scale of distances in the entire solar system.

The planetary orbits are, in reality, from twenty to thirty times wider than the astronomers of the time of Horrox conceived them. The full significance of the disparity between the contemporary view and the inspired estimate of the young English genius will be evident only if we recall that Galileo survived Horrox by a year, that Kepler had passed from the scene only a decade earlier, and that the keen-eyed Hevelius was then in his prime.

A younger generation of astronomers was about to come to

the fore, however, several of whose members would take up the problem of the sun's distance, for the first time giving official challenge, as it were, to the altogether faulty conception, traditional from the day of Aristarchus, which placed the sun only eighteen or twenty times (instead of about 145 times) as far from the earth as the moon.

FIG. 34.—John Flamsteed (1646-1719), First Astronomer Royal of England. (Redrawn from Bryant's *History of Astronomy.* Original Source not Stated.)

The relative distances of the various planets were, of course, correctly known, in accordance with Kepler's Laws, but the absurdly mistaken estimate as to the unit distance, the radius of the earth's orbit, made the scale of the solar system, as authoritatively accepted, like a miniature replica of the actual planetary system.

The Englishman, Flamsteed, first Astronomer Royal, and the

Frenchmen, Cassini and Richer, acting in unison in 1672, were chiefly responsible for new observations, directed to the planet Mars in opposition, through which the age-old error was corrected, and something like the real magnitude of the solar system revealed, to the amazement of the astronomical world and the intellectual public in general.

It is illuminating to recall that the generation which thus for the first time in the history of the world had the remotest conception of the actual magnitude of the planetary system of which our earth is a part, included such geniuses of the scientific world as Newton, Huygens, Hooke, and Leibnitz. The cultural aspects of the time may be envisaged by recalling that this is the age of three of England's most celebrated writers—Bunyan, Dryden, and Milton.

The fall of Lucifer, on that famed summer's day, as Milton conceived it, compassed but a small fraction of the abysmal distances which, only five years later (for "Paradise Lost" was published in 1667) were to be revealed by the telescopes of the inspectors of Mars as the actual confines of the Solar system, at that time still commonly regarded as practically the confines of the universe.

The Parallax Observations

It should be added, however, that the astronomers who made the new measurement were well aware that a very wide distance separates the planetary system from the vault of the firmament in which the fixed stars are located. They had no very clear conception as to the actual nature of the fixed stars themselves, but the fact that those stars showed no shift of position when viewed from opposite sides of the earth's orbit (for by now the astronomical leaders were convinced of the truth of the Copernican doctrine) proved their vast distance—even though the earth's

orbit was supposed to be a fraction as wide as the new measurements were to reveal it.

The method of making these measurements, indeed, was based on the fact that the stars of the firmament appear fixed in their places, and therefore can be used as a background against which the relatively nearby planet Mars is projected.

If observation is made of the planet's relation to some nearby star or stars at a given time and place of observation, and then a subsequent observation, when the observer's position has been shifted eastward by the earth's rotation, is made of the same objects, the apparent shift of position of the planet (allowance being made, of course, for actual movement in its orbit) will give data for the kind of angular or trigonometric measurement, by which distance of the observed object may be determined.

The same object will be accomplished if two observers situated at widely separated points make simultaneous telescopic tests of the exact position of the planet in relation to the background of stars. Here the distance between the places of observation furnishes the base line, precisely as it was furnished by the shifted position of the single observer; with the advantage that now there is no calculation to be made as to the actual movement of the planet.

Such observations may obviously be made to best advantage in a region at or near the equator. The equatorial region of Africa being inpenetrable, the Mars-testing campaign of the coalition of astronomers in 1672 (as well as many similar campaigns of later history) involved a journey to South America.

What the Tests Revealed

The results of the tests were as accurate as could be expected with the relatively crude instruments then available.

A parallax of about ten seconds was revealed—an incredible

figure in view of the estimates hitherto accepted as valid and recorded in supposedly authoritative tables.

Even Kepler, who regarded the conventional figure of 180 seconds as grossly inaccurate, was content to assert that he believed the actual parallax could not be greater than 60 seconds. Horrox, as we have seen, had improved vastly on this estimate, with his suggestion of a fourteen second estimate. The observers of Mars—making the first parallax determinations that could be said to have any considerable measure of scientific validity, reduced the figure to about ten seconds. (The modern estimate, as we shall see, is a little more than one second smaller—8.8 or thereabouts.)

Thus, at a single coup, and perhaps to their own bewilderment, the three Mars-testing astronomers were obliged, in deference to their own observations, to hurl the sun away from the earth, to a distance twenty times that at which it had been supposed to be stationed—landing it at the inconceivable distance of something like eighty million miles, as against the neighborly four million miles it had hitherto occupied.

And if the sun was moved twenty times as far away as it hitherto had been supposed to be stationed, it was by the same token increased twenty times in diameter.

It must be four hundred times, not merely twenty times, as wide as the moon. That made it enormously larger than the earth, and went far to justify the location at the centre of the universe, where the Copernican conception places it.

So, after all, the heliocentric doctrine is not quite so absurd as it has seemed.

The average man has a strong bent for practicality. Ordinary imagination goes little beyond ordinary experience. One can con-

Influence of the New Knowledge

ceive bodies whirled about by large ones better than one can conceive the reverse condition. So perhaps we shall not be far wrong if we assume that the new measurements of the distance of the sun, made by three astronomers of high repute in the year 1672, and accepted at once by the majority of their confrères, may have gone farther toward reconciling the contemporary generation to the conception of a heliocentric world than all other scientific influences put together.

The average man could know nothing of Kepler's laws of planetary motion; he could have but scant comprehension of Galileo's laws of physical motion here at the earth's surface; still less comprehend the import of Newton's presently forthcoming law of universal gravitation.

But he could clearly recognize the plausibility of placing a big body instead of a small body at the center of any system of revolving machinery. And the bald statement that the sun is a gigantic ball and the earth a relative dwarf is one that he could clearly grasp.

Of course, I do not mean to imply that the average man, even though he heard so strange a thing reported, and could clearly apprehend the meaning of what he heard, accepted the new knowledge at once as matter for belief.

To make that assumption would be to run counter to all history.

But the Copernican doctrine could not have been before the world for four or five generations (since 1543) without gaining some converts.

It was still heresy, of course. No conscientious churchman of the ultramontane faith could so much as read about it, let alone speak of it—for the works not alone of Copernicus but of Kep-

ler and Galileo had of course been placed on the *Index* (there to remain yet another 150 years); and equally, of course, tradition still kept its hold on the educational institutions and their textbooks. But the leaven of truth ultimately leavened the popular mind, despite such conventional obstacles, and the form of truth which has, naturally, most quickening power, is that which appeals to the understanding of the masses of mankind.

The measurement of a planet, by methods that any surveyor can understand, held possibilities of popular enlightenment to which the formulae of a Newton cannot aspire.

And as yet Newton had not put forth his formulae. But at the time when the parallax measurements were made, he was on the scene, approaching full maturity of mind. Nor was it by any means an accident that his mind should be directed primarily toward the explanation of the mechanism of the universe, in an age when the physical proportions and true relations between the bodies of the planetary system were being revealed and so ardently investigated.

We shall learn, perhaps with surprise, that this great mathematical genius was no less visually-minded than the observing astronomers; and that he was led to his greatest discovery—generally appraised as the greatest discovery of all time—through consideration of the practical relationships of the planetary bodies; and tested and demonstrated his conception of universal gravitation by consideration of the tangibilities of the moon's motion, which one need not be at all a mathematician fully to comprehend.

We turn now to the story of this greatest of geniuses, and his monumental discovery.

XIII

THE COMING OF NEWTON

On Christmas day of the year in which great Galileo died (1642), there was born in England another intellectual giant who was destined to carry forward the work of Copernicus, Kepler, and the heretical Italian, to a marvellous consummation through the discovery of the all-compassing law in accordance with which the planetary motions are performed.

I refer, of course, to the greatest of English physical scientists, Isaac Newton, the Shakespeare of the scientific world.

Born thus before the middle of the seventeenth century, Newton lived beyond the first quarter of the eighteenth (1727). For the last forty years of that period his was the dominating scientific personality of the world. With full propriety that time has been spoken of as the "Age of Newton."

Yet the man who was to achieve such distinction gave no early premonition of future greatness.

He was a sickly child from birth, and a boy of little seeming promise. He was an indifferent student. On the other hand, he cared little for the common amusements of boyhood. He early exhibited, however, a taste for mechanical contrivances, and spent much time in devising windmills, water-clocks, sun-dials, and kites.

While other boys were interested only in having kites that would fly, Newton—at least so the stories of a later time would have us understand—cared more for the investigation of the seeming principles involved, or for testing the best methods of

attaching the strings, or the best materials to be used in construction.

Meanwhile the future philosopher was acquiring a taste for reading and study, delving into old volumes whenever he found an opportunity.

These habits convinced his relatives that it was useless to attempt to make a farmer of the youth, as had been their intention. He was therefore sent back to school, and in the summer of 1661 he matriculated at Trinity College, Cambridge. Even at college Newton seems to have shown no unusual mental capacity, and in 1664, when examined for a scholarship by Dr. Barrow, that gentleman is said to have formed a poor opinion of the applicant.

It is said that the knowledge of the estimate placed upon his abilities by his instructor piqued Newton, and led him to take up in earnest the mathematical studies in which he afterwards attained such distinction.

The study of Euclid and Descartes' *Geometry* roused in him a latent interest in mathematics, and from that time forward his investigations were carried on with enthusiasm. In 1667 he was elected Fellow of Trinity College, taking the degree of M.A. the following spring.

It will thus appear that Newton's boyhood and early manhood were passed during that troublous time in British political annals which saw the overthrow of Charles I., the autocracy of Cromwell, and the eventual restoration of the Stuarts. His maturer years witnessed the overthrow of the last Stuart and the reign of the Dutchman, William of Orange. In his old age he saw the first of the Hanoverians mount the throne of England. Within a decade of his death such scientific path-finders as Cavendish,

Black, and Priestley were born—men who lived on to the close of the eighteenth century.

In a full sense, then, the age of Newton bridges the gap from that early time of scientific awakening under Kepler and Galileo to the time which we of the twentieth century think of as essentially modern.

The Composition of White Light

In December, 1672, Newton was elected a Fellow of the Royal Society, and at this meeting a paper describing his invention of the reflecting telescope was read.

A few days later he wrote to the secretary, making some inquiries as to the weekly meetings of the society, and intimating that he had an account of an interesting discovery that he wished to lay before the members. When this communication was made public, it proved to be an explanation of the discovery of the composition of white light.

The question as to the nature of color had commanded the attention of such investigators as Huygens, but no very satisfactory solution had been attained.

Newton proved by demonstrative experiments that white light is composed of the blending of the rays of diverse colors, and that the color that we ascribe to any object is merely due to the fact that the object in question reflects rays of that color, absorbing the rest.

That white light is really made up of many colors blended would seem incredible had not the experiments by which this composition is demonstrated become familiar to every one. The experiments were absolutely novel when Newton brought them forward, and his demonstration of the composition of light was one of the most striking expositions ever brought to the attention of the Royal Society.

It is hardly necessary to add that, notwithstanding the conclusive character of Newton's work, his explanations did not for a long time meet with general acceptance.

Newton was led to his discovery by some experiments made with an ordinary glass prism applied to a hole in the shutter of a darkened room, the refracted rays of the sunlight being received upon the opposite wall and forming there the familiar spectrum.

"It was a very pleasing diversion," he wrote, "to view the vivid and intense colors produced thereby; and after a time, applying myself to consider them very circumspectly, I became surprised to see them in varying form, which, according to the received laws of refraction, I expected should have been circular. They were terminated at the sides with straight lines, but at the ends the decay of light was so gradual that it was difficult to determine justly what was their figure, yet they seemed semicircular."

This "ordinary glass prism" was to play an extraordinary part in the astronomical development of a later century. But as yet its future rôle was quite unsuspected. We need not here follow the discovery of the spectrum farther. We shall hear more about the beam of light—and in particular some of its strange features that Newton overlooked—in a later chapter.

Here we press on at once to the discovery that constitutes the greatest single contribution ever made to pure science; a discovery as meaningful for astronomy as had been the invention of the telescope itself.

The Law of Gravitation

I refer, of course, to the law of gravitation, the most far-reaching principle ever hitherto discovered.

This law has application to the minutest particle of matter

in the earth's structure, and to the most distant suns in the universe.

Yet it is amazing in its simplicity.

As usually phrased, the law is this: *Every particle of matter in the universe attracts every other particle with a force that varies directly with the product of the masses of the particles and inversely as the squares of their mutual distance.*

Newton did not vault at once to the full expression of this law, though he had formulated it fully before he gave the results of his investigations to the world. We have now to follow the steps by which he reached this culminating achievement.

At the very beginning we must understand that the idea of universal gravitation was not absolutely original with Newton.

Away back in the old Greek days, Anaxagoras conceived and clearly expressed the idea that the force which holds the heavenly bodies in their orbits may be the same that operates upon substances at the surface of the earth.

With Anaxagoras this was scarcely more than a guess. After his day the idea seems not to have been expressed by any one until the seventeenth century's awakening of science. Then the consideration of Kepler's Third Law of planetary motion suggested to many minds perhaps independently the probability that the force hitherto mentioned merely as centripetal, through the operation of which the planets are held in their orbits, is a force varying inversely as the square of the distance from the sun. This idea had come to Robert Hooke, to Wren, and perhaps to Halley, as well as to Newton; but as yet no one had conceived a method by which the validity of the suggestion might be tested.

It was claimed later by Hooke that he had discovered a method of demonstrating the truth of the theory of inverse squares, and

after the full announcement of Newton's discovery a heated controversy was precipitated in which Hooke put forward his claims with accustomed acrimony. Hooke, however, never produced his demonstration, and it may well be doubted whether he found a method which did more than vaguely suggest the law which the observations of Kepler had partially revealed.

Newton's great merit lay not so much in conceiving the law of inverse squares as in the demonstration of the law.

He was led to this demonstration through considering the orbital motion of the moon.

The Apple Story

According to the familiar story, which has become one of the classic myths of science, Newton was led to take up the problem through observing the fall of an apple.

Voltaire is responsible for the story, which serves as well as another; its truth or falsity need not in the least concern us. Suffice it that through pondering on the familiar fact of terrestrial gravitation, Newton was led to question whether this force which operates so tangibly here at the earth's surface may not extend its influence out into the depths of space, so as to include, for example, the moon.

Obviously some force pulls the moon constantly towards the earth; otherwise that body would fly off at a tangent and never return.

May not this so-called centripetal force be identical with terrestrial gravitation?

Such was Newton's query. Probably many another man since Anaxagoras had asked the same question, but assuredly Newton was the first man to find an answer.

The thought that suggested itself to Newton's mind was this: If we make a diagram illustrating the orbital course of the moon

for any given period, say one minute, we shall find that the course of the moon departs from a straight line during that period by a measurable distance—that is to say, the moon has been virtually pulled towards the earth by an amount that is represented by the difference between its actual position at the end of the minute

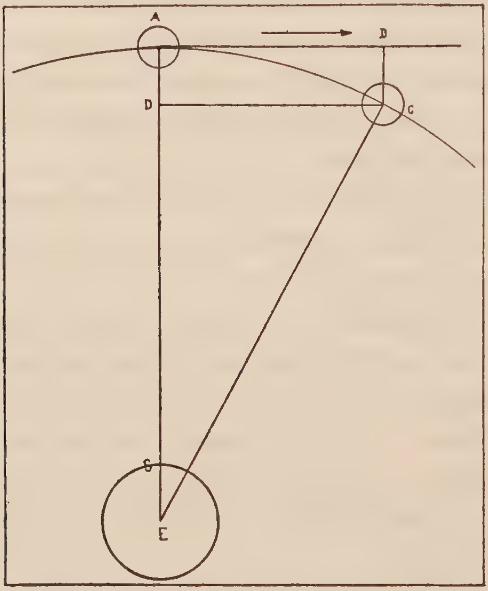

FIG. 35.—Newton's Demonstration of Gravitation Between Earth and Moon. (From Williams' *History of Science.*) See text for explication.

under observation and the position it would occupy had its course been tangential, as, according to the first law of motion, it must have been had not some force deflected it towards the earth.

Measuring the deflection in question—which is equivalent to the so-called versed sine of the arc traversed—we have a basis for determining the strength of the deflecting force.

Newton constructed such a diagram, and, measuring the

amount of the moon's departure from a tangential rectilinear course in one minute, determined this to be, by his calculation, thirteen feet.

Obviously, then, the force acting upon the moon is one that would cause that body to fall towards the earth to the distance of thirteen feet in the first minute of its fall. Would such be the force of gravitation acting at the distance of the moon if the power of gravitation varies inversely as the square of the distance?

That was the tangible form in which the problem presented itself to Newton.

The mathematical solution of the problem was simple enough. It is based on a comparison of the moon's distance with the length of the earth's radius. On making this calculation, Newton found that the pull of gravitation—if that were really the force that controls the moon—gives that body a fall of slightly over fifteen feet in the first minute, instead of thirteen feet.

Here was surely a suggestive approximation. On the other hand, the discrepancy seemed to be too great to warrant him in the supposition that he had found the true solution.

He therefore dismissed the matter from his mind for the time being, nor did he return to it definitely for some years.

A New Survey Gives Correct Data

It was to appear in due time that Newton's hypothesis was perfectly valid and that his method of attempted demonstration was equally so.

The difficulty was that the earth's proper dimensions were not at that time known. A wrong estimate of the earth's size vitiated all the other calculations involved, since the measurement of the moon's distance depends upon the observation of

the parallax, which cannot lead to a correct computation unless the length of the earth's radius is accurately known.

Newton's first calculation was made as early as 1666, and it was not until 1682 that his attention was called to a new and apparently accurate measurement of a degree of the earth's meridian made by the French astronomer Picard. The new measurement made a degree of the earth's surface 69.10 miles, instead of sixty miles.

Learning of this materially altered calculation as to the earth's size, Newton was led to take up again his problem of the falling moon.

As he proceeded with his computation, it became more and more certain that this time the result was to harmonize with the observed facts. As the story goes, he was so completely overwhelmed with emotion that he was forced to ask a friend to complete the simple calculation. That story may well be true, for, simple though the computation was, its result was perhaps the most wonderful demonstration hitherto achieved in the entire field of science.

Now at last it was known that the force of gravitation operates at the distance of the moon, and holds that body in its elliptical orbit. It required but a slight effort of the imagination to assume that the force which operates through such a reach of space extends its influence yet more widely.

That such is really the case was demonstrated presently through calculations as to the moons of Jupiter and by similar computations regarding the orbital motions of the various planets.

All results harmonizing, Newton was justified in reaching the conclusion that gravitation is a universal property of matter.

It remained, as we shall see, for nineteenth-century astrono-

Plate VIII: ISAAC NEWTON (1642-1727)
(Crow-quill composite, costume chiefly based on the painting by Sir Godfrey Kneller, as reproduced in an engraving by Jacob Houbracken, and photogravured in Appleton's *Essays in Astronomy*)

mers to prove that the same force actually operates upon the stars, though it should be added that this demonstration merely fortified a belief that had already found full acceptance.

Did the new theory, then, find immediate acceptance? Far from it. This was not the age of miracles.

Opposition to the New Law

Opposition had of course been foreseen by Newton, and, much as he dreaded controversy, he was prepared to face it and combat it to the bitter end. He knew that his theory was right; it remained for him to convince the world of its truth. He knew that some of his contemporary philosophers would accept it at once; others would at first doubt, question, and dispute, but finally accept; while still others would doubt and dispute until the end of their days.

This had been the history of other great discoveries; and this will probably be the history of most great discoveries for all time.

Delambre is authority for the following estimate of Newton by Lagrange.

"The celebrated Lagrange," he says, "who frequently asserted that Newton was the greatest genius that ever existed, used to add—'and the most fortunate, for we cannot find *more than once* a system of the world to establish.' "

With pardonable exaggeration the admiring followers of the great generalizer pronounced this epitaph:

> "Nature and Nature's laws lay hid in night;
> God said 'Let Newton be!' and all was light."

The Contemporary Verdict

But these, be it understood, were not contemporary verdicts. Not for a moment must it be supposed that Newton's confrères accepted his theory unanimously, nor that within a generation or two, his law found universal acceptance.

On the contrary, there was outcry against the doctrine of universal gravitation as "atheistic," notwithstanding the known piety of its author. To suggest that the forces of this corrupt abode of fallen man extend out to control the immaculate celestial spheres, smacked of sacrilege.

In orthodox France, the famous Cassini (1626-1712), director of the Paris Observatory, never openly acknowledged the Copernican doctrine. The eminent mathematician Boscovich, expositing the Newtonian thesis, felt it necessary or expedient to shield himself with these prefatory words:

"As for me, full of respect for the Holy Scriptures and the decrees of the Holy Inquisition, I regard the earth as immovable. Nevertheless, for simplicity in explanation, I will argue as if the earth moves; for it is proved that of the two hypotheses the appearances favor this idea."

This was in the year 1751, more than two centuries after the death of Copernicus, and 65 years after the publication of the *Principia*.

Yet later, in 1765, another famous French astronomer, Lalande, tried in vain at Rome to induce the authorities to remove Galileo's works from the *Index*. Bossuet, the great Bishop of Meaux (d. 1704) decreed the idea of the earth's motion to be contrary to Scripture some years after the work of Newton had been published. Many universities prohibited the study of the Newtonian system for yet another century.

E pur si muove?

Perhaps. But mother earth's inhabitants seem little disposed to imitate her example.

BOOK IV

E PUR SI MUOVE

"The world also is established that it cannot be moved."

—*Oriental Anthology.*

"The opinion of the earth's motion is of all heresies the most abominable, the most pernicious, the most scandalous; the immovability of the earth is thrice sacred; argument against the immortality of the soul, the existence of God, and the incarnation, should be tolerated sooner than an argument to prove that the earth moves."

—*Father Melchior Inchofer.*

"E pur si muove."

—*Galileo Galilei.*

XIV

HUYGENS—HEVELIUS—ROEMER—WHAT BETTER TELESCOPES REVEALED

THE astronomical world is peculiarly indebted to the man who invented the pendulum clock, Christian Huygens (1629-1695), of the Hague, inventor, mathematician, mechanician, astronomer, and physicist.

Huygens was the descendant of a noble and distinguished family, his father, Sir Constantine Huygens, being a well-known poet and diplomatist. Young Huygens began his career in the legal profession, completing his education in the juridical school at Breda. But his taste for mathematics soon led him to neglect his legal studies.

He showed such enthusiasm, imagination, and mechanical aptitude that Descartes predicted great success for him at the very outset of his career.

One of his first endeavors in science was to attempt an improvement of the telescope.

Reflecting upon the process of making lenses then in vogue, young Huygens and his brother Constantine attempted a new method of grinding and polishing, and introduced a two-lens eye-piece (still called a Huygens ocular), that enlarges the field, and somewhat compensates chromatic aberration.

With this new telescope a much clearer field of vision was obtained, so that Huygens was able to detect, among other things, a hitherto unknown satellite of Saturn.

It was these astronomical researches that led him to apply the pendulum to regulate the movements of clocks. The need for some more exact method of measuring time in his observations of the stars was keenly felt by the young astronomer, and after several experiments along different lines, Huygens hit upon the use of a swinging weight; and in 1656 made his invention of the pendulum clock.

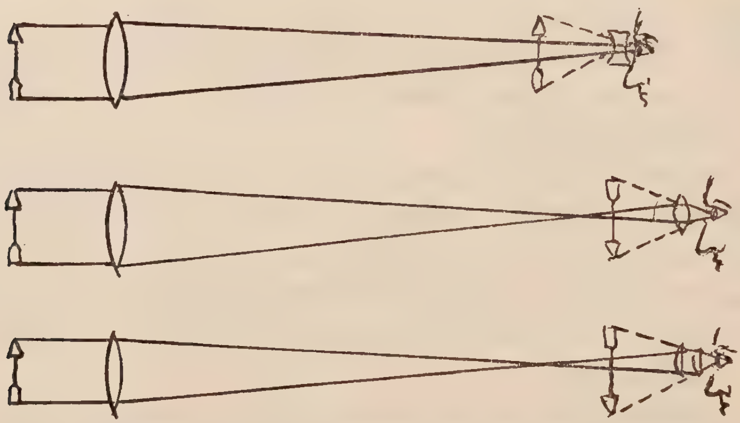

FIG. 36.—Three Types of Eyepieces or Objectives. Top figure, the concave lens of Galileo's telescope. Middle figure, Kepler's convex eye-piece. Lower figure, the double plano-convex lens of the Huygens eye-piece.

The year following, his clock was presented to the states-general.

The First Accurate Clock

Accuracy as to time is absolutely essential in astronomy, but until the invention of Huygens's clock there was no precise, nor even approximately precise, means of measuring short intervals.

Huygens was one of the first to adapt the micrometer to the telescope—a mechanical device on which all the nice determination of minute distances depends. He also took up the controversy against Hooke as to the superiority of telescopic over plain

sights to quadrants, Hooke contending in favor of the plain. In this controversy, the subject of which attracted wide attention, Huygens was completely victorious.

He pointed out that the unaided eye is unable to appreciate an angular space in the sky less than about thirty seconds. Even

FIG. 37.—Christian Huygens (1629-1695). (Adapted from Bell's *The Telescope*. There the source is not credited.)

in the best quadrant with a plain sight, therefore, the altitude must be uncertain by that quantity. If in place of the plain sight a telescope is substituted, even if it magnify only thirty times, it will enable the observer to fix the position to one second, with progressively increased accuracy as the magnifying power of the telescope is increased.

In the field of optics, also, Huygens has added considerably to

science, and his work, *Dioptrics,* is said to have been a favorite book with Newton.

Bigger and Better Telescopes

During the later part of his life, however, Huygens again devoted himself to inventing and constructing telescopes, grinding the lenses, and devising, if not actually making, the frame for holding them.

These telescopes were of enormous lengths, three of his object-glasses, now in possession of the Royal Society, being of 123, 180, and 210 feet focal length respectively. Such instruments, if constructed in the ordinary form of the long tube, were unmanageable, and to obviate this Huygens adopted the plan of dispensing with the tube altogether, mounting his lenses on long poles manipulated by machinery.

Even these were unwieldy enough, but the difficulties of manipulation were fully compensated by the results obtained.

In the construction of his telescope Galileo had made use of a convex and a concave lens; but shortly after this Kepler invented an instrument in which both the lenses used were convex. This telescope gave a much larger field of view than the Galilean telescope, but did not give as clear an image, and in consequence did not come into general use until the middle of the seventeenth century.

The first powerful telescope of this type was made by Huygens and his brother.

The Micrometer of Huygens

It was of twelve feet focal length, and enabled Huygens to discover a new satellite of Saturn, and to determine also the true character of Saturn's ring.

It was Huygens, together with Malvasia and Auzout, who first applied the micrometer to the telescope, although the first microm-

eter was devised by William Gascoigne, of Yorkshire, about 1636.

The micrometer as used in telescopes enables the observer to measure accurately small angular distances. Before the invention of the telescope such measurements were limited to the angle that could be distinguished by the naked eye, and were, of course, only approximately accurate. Even so famed an observer as Tycho Brahe was able to obtain results accurate only within about two minutes of arc. But by applying Gascoigne's invention to the telescope far greater accuracy became at once possible.

The principle of Gascoigne's micrometer was that of two pointers lying parallel, and in this position pointing to zero. These were arranged so that the turning of a single screw separated or approximated them at will, and the angle thus formed could be determined with a high degree of accuracy.

Huygens' micrometer was a slip of metal of variable breadth inserted at the focus of the telescope. By observing at what point this exactly covered an object under examination, and knowing the focal length of the telescope and the width of the metal, he could then deduce the apparent angular breadth of the object. Huygens discovered also that an object placed in the common focus of the two lenses of a Kepler telescope appears distinct and clearly defined.

Other Types of Micrometers

The micrometers of Malvasia, and later of Auzout and Picard, are the development of this discovery.

Malvasia's micrometer, which he described in 1662, consisted of fine silver wires placed at right-angles at the focus of his telescope.

As telescopes increased in power, however, it was found that even the finest wire, or silk filaments, were much too thick for

astronomical observations, as they obliterated the image, and so, finally the spider-web came into use and is still used in micrometers and other similar instruments.

Before that time, however, the fine crossed wires had revolutionized astronomical observations.

"We may judge how great was the improvement which these

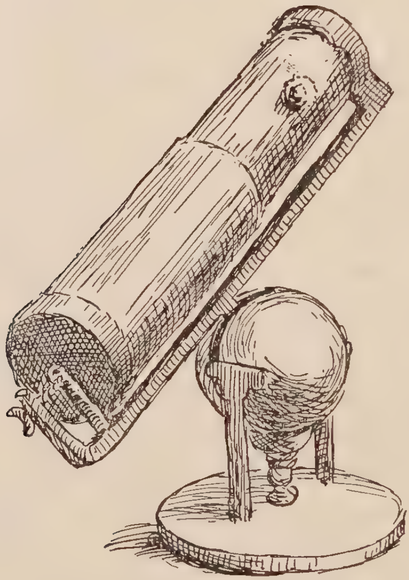

FIG. 38.—Newton's Model of a Reflecting Telescope.

contrivances introduced into the art of observing," says Whewell, "by finding that Hevelius refused to adopt them because they would make all the old observations of no value. He had spent a laborious and active life in the exercise of the old methods, and could not bear to think that all the treasures which he had accumulated had lost their worth by the discovery of a new mine of richer ones."

Newton's Reflecting Telescope

Until the time of Newton, all the telescopes in use were either of the Galilean or Keplerian type, that is, refractors.

But about the year 1670 Newton constructed his first reflecting telescope, which was greatly superior to, although much smaller than, the telescopes then in use. He was led to this invention by his experiments with light and colors.

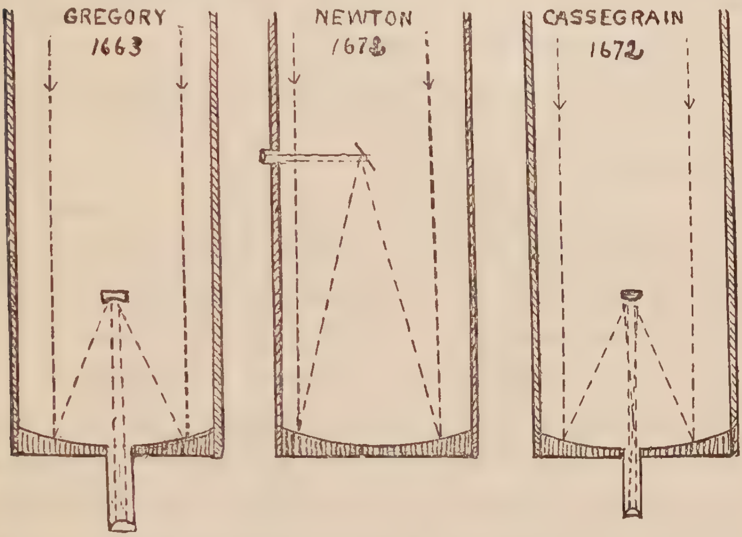

Fig. 39—Three Types of Reflecting Telescopes. The rays of light focussed by the large concave mirror are reflected to the eye-piece by small mirrors that are respectively concave (parabolic), plane, and convex (hyperbolic) in the successive types as depicted.

In 1671 he presented to the Royal Society a second and somewhat larger telescope; and this type of instrument was little improved upon until the introduction of the achromatic telescope, invented by Chester Moor Hall, in 1733.

The Frenchman Cassegrain invented a reflecting telescope independently of Newton at about the same time. But the reflectors

were not to come to full maturity, so to speak, for another century.

As a matter of course, new discoveries followed the train of the improved instruments of observation. Huygens, for example, not only discovered a new satellite of Saturn, as above mentioned, but was able to interpret the curious markings of this planet, which had so puzzled Galileo. Huygens explained that a solid ring surrounded the planet.

He met skepticism by declaring that this was something that he had seen—not something invented, like the epicycles of the old astronomers.

Soon after, the French astronomer Cassini discovered that there is a division in the ring of Saturn, making it double. The memoir of the Académie des Sciences, in announcing this discovery, has an aside to the effect that "in the heavens as well as on the earth, something new to observe always appears."

Roemer Measures the Speed of Light

This was interesting, but an astronomical observation of far greater importance was made at about the same period by Olaus Roemer, Danish astronomer, working at the Paris Observatory.

He had been struck by the irregularity of appearance of the first satellite of Jupiter, in emerging from the shadow of its parent body, or in entering the shadow when viewed from the other side. It occurred to him that here was a possible opportunity to test the much mooted question as to whether light travels through the universe instantaneously.

If the transit of light be not instantaneous, he reasoned, the rate of its speed might be tested by observing the occultation of the satellite from different regions of the earth's orbit, assuming of course that the satellite itself revolves with perfect regu-

larity—its observed and calculated time of revolution being about forty-two and one-half hours.

The first tests were not successful. That is to say, they did not show the expected difference. But they were made at the interval of only a single revolution of the satellite; and there-

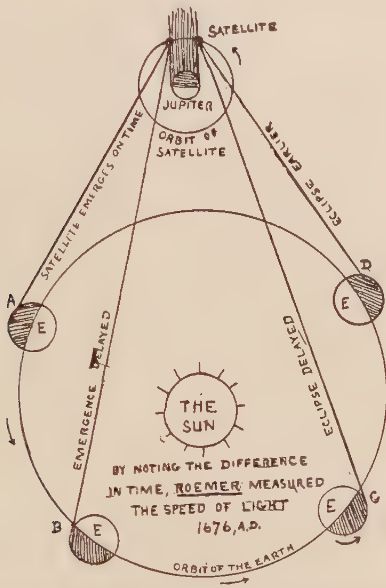

Fig. 40.—To Illustrate Roemer's Proof of the Finite Speed of Light.

fore timed the transit of light only through the distance of less than two days' flight of the earth itself.

When, subsequently, the test was made again, with a longer interval of time, so that in effect the time of transit of light across the entire orbit of the earth was in question, a difference was observed, which Roemer estimated as twenty-two minutes.

He correctly inferred that light had required an appreciable time to cross the orbit of the earth, though his measurement was

not precise. Later observations gave sixteen minutes and thirty-seven seconds as the time required by light to pass the distance of the earth's orbital diameter. This gives about 186,000 miles per second as the speed of light—a highly important "constant" for use of future observers.

This major discovery immortalized the name of the Danish astronomer. We shall see that application of the principle led to other major discoveries almost immediately.

In itself, the discovery evidenced once more that "something new is always appearing," and supported from another angle the growing conviction that the entire heavenly mechanism is subject to "natural" laws.

XV

EDMUND HALLEY—UNMASKING THE COMET

AND now another youthful prodigy appears. Edmund Halley, son of a wealthy soap-manufacturer, sends a first paper to the Royal Society at the age of nineteen years.

This was in the year 1675. The young astronomer was elected a Fellow of the Royal Society at the age of twenty-two.

Thereafter, throughout a long life, Halley was to be universely known not only as a man of genius but as one of the most delightful personalities of his generation. On the death of Flamsteed he succeeded in 1721 to the position of Astronomer Royal, and although at that time in his sixties, he held the position

with honor, and continued active in astronomical work for twenty years.

Throughout the middle period of his life, Halley was a marked man, even in the age of Newton. After Newton's death, he was the foremost figure of the English astronomical world, only rivaled by his younger confrère, and subsequent successor as Astronomer Royal, James Bradley.

Halley's fame is adequately supported by his own discoveries, but he is known also with high honor for having been largely responsible for the publication of Newton's epoch-making work, the expenses of which he bore. As friend of Newton and protagonist of his theory, as Savilian Professor at Oxford, as Secretary of the Royal Society, and as Royal Astronomer, he proved everywhere not only his genius but the innate high-mindedness and stability of character that are attributes of true greatness.

In precocity of genius, Halley was comparable to Horrox before and Olbers after him. He derived his first fame at nineteen or twenty by devising a new formula for calculating the orbits of planets. This was the paper that won him recognition from the Royal Society.

The following year he went to St. Helena to study the southern sky. His observations were so varied and accurate, and his speculations so cogent, as to lead Flamsteed, then Astronomer Royal and a leading figure of the scientific world, to speak of the young astronomer as "the Tycho of the south."

In after times Halley was to be universally known as having predicted the exact time of the next transit of Venus, and having accomplished the even more striking feat of calculating the orbit of a comet, and predicting the time of its return.

It was in the year 1716, in a paper presented before the Royal

The Predicted Transit of Venus

Society, that Halley made the famous prediction as to the transit of Venus, to take place in the year 1761.

The prediction was notable, not merely as illustrating accurate knowledge of the orbit of Venus, but in particular because of the astronomers' speculations as to the probable value of observations of the transit in determining the still doubtful question of the sun's exact parallax.

Halley was led to speculate on this subject, apparently, by his own observations of a transit of Mercury, made at St. Helena, forty years earlier. He reports that he was then able to note the precise second at which the planet came in contact with the sun's limb, and also the precise second of exit. But he further reflects that, owing to the relatively slight difference between the distance of the sun and Mercury from the earth, observations of transit of Mercury would not be of great value for determining parallax.

The location of Venus, on the other hand, its orbit being so much nearer the earth, would permit, Halley predicted, such observations as would enable the calculation of the sun's parallax to be made with a high degree of accuracy.

Nothing more would be necessary, he pointed out, than the use of good ordinary clocks, to determine the precise moment when the planet was observed to make contact with the sun's limb, or exit from it. It would be necessary, of course, to have similar observations made by astronomers at different locations of the earth, for comparison of the times of contact.

Halley forecast in detail what locations would be favorable for such observations, naming points in the tropics on one hand and in the arctic zone on the other.

The principle involved will be clearly understood if you will

Plate IX: Edmond Halley (1656-1742)
(Pencil, crayon and body-color interpretation and adaptation from the painting by Dahl in the possession of the Royal Society of England, as reproduced by an unknown engraver, and half-toned in Williams' *History of Science*)

The Transit-Parallax Method Illustrated

think of two persons standing a few feet apart at one side of a room while any object is moved, say in the hand of a third person, across the middle of the room at right angles to the line of vision. The moment when the moving object lies directly in line with some mark on the opposite wall will be different for the two observers.

An even simpler, and perhaps more striking illustration of

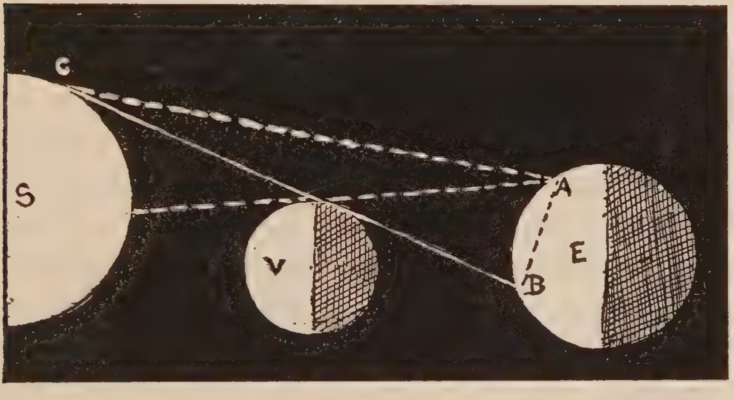

Fig. 41.—To Illustrate Halley's Parallax Method. The observers at A and B see the planet touch the limb of the sun at different times and crossing the sun's face in different solar latitudes. The base-line AB and the measured angles at A and B are the data for "triangulation" of the sun's distance.

the same thing is given if you will merely hold up a finger and, closing your right eye, bring the finger tip against some object at the far side of the room. Now close your left eye and open the right one, and you will see at once that the finger point lies well to the left of the focal object, and must be moved forward a certain distance to come in contact with it. When such contact is made, if you close the right eye and open the left one, the

finger will seem to shift suddenly to the right by a corresponding distance.

It will be obvious that the distance between the two observers in the first illustration, or between your two eyes in the second, will constitute a base line forming one side of a triangle, the other two sides being the respective lines-of-sight from the two positions to the object on the wall. If the angles between the two lines of sight and the base line are measured, it is a very simple problem in triangulation to determine the distance of the object on the wall from the base line.

In making the transit-of-Venus observation, the radius of the earth is regarded as the base line. Observations may not be made by different persons at precisely the distance apart of the earth's radius, but the known actual distance can readily be transformed by mathematical calculation to the equivalent of the radius.

The angle thus determined—in effect the angle that the earth's radius would subtend as viewed from the sun—is known as the sun's parallax.

Almost twenty years after Halley's death, Venus made the transit of the sun as predicted, and many observers were waiting to test the method the great astronomer had recommended. The results were not quite as satisfying as Halley had confidently expected, it being found difficult to note the precise moment when the disk of the planet coincides with the not very sharply defined disk of the sun. Still more difficult to judge when the planet is exactly at the sun's centre.

The Sun's Distance

Even so, the transit observations gave by far the best data for calculating the sun's distance theretofore available.

Particular interest attaches to the statements made by Halley

at the time of his prediction (1715), as to the estimates then current regarding the sun's distance.

He mentions that Ptolemy, back in the old Greek days, and the relative moderns, Copernicus and Tycho, had accepted 1200 semi-diameters of the earth as the sun's distance—making the distance about 4,800,000 miles, and the Italian Riccioli doubled this distance. Hevelius, on the other hand, the great Danish observer, was disposed to cut the distance in half—bringing the sun within about 7,000,000 miles of the earth.

It is stated by Halley, however, that "some modern," observing with the telescope that Venus and Mercury on the sun's disk were proportionately smaller than had been supposed, have extended the distance greatly, bringing it up to about 56,000,000 miles.

Meantime the reflection that smaller distances would imply that Mercury is not so large as our moon—"a secondary planet larger than a primary one, which seems repugnant to the regular proportion and symmetry of the mundane system"—makes it seem possible that the distance is even greater.

Halley's own provisional estimate is about twelve and a half seconds, which would permit us to estimate the moon as a little less than Mercury. (The actual sizes, by modern measurement, are: Mercury, 3009 miles in diameter; the moon, 2160 miles.) The sun's distance from the earth then comes out at 16,500 semi-diameters of the earth—or about 66,000,000 miles.

This discussion, it will be noted, took place twenty-nine years after the publication of Newton's *Principia,* and represented the estimate of the man who had been largely responsible for the publication of Newton's work, and who certainly was as competent as any other person living to make such an estimate.

On the highest possible authority, then, we know that the largest figure hitherto named as the distance of the earth from the sun, was 66,000,000 miles—not much over two-thirds the actual distance (92,897,400 miles) as determined by several methods in subsequent years.

It has been more than once explained that relative distances in the sun's planetary system are known by Kepler's laws, regardless of actual distances. There are many reasons, however, why it is desirable to know the actual length of the sun-to-earth yardstick, generally used as the unit of measurement. And it is rather surprising to learn that all distances in the solar system, except the distance of the moon, are about fifty percent greater than Newton and Halley and their confrères regarded them. The diameters of the planetary orbits had been magnified more than sixteen-fold since the time of Copernicus and Tycho. But even yet it was not possible to appraise the solar system at anything like its correct dimensional value.

By the same token, the actual dimensions of the sun and of all the planetary bodies except the earth and moon, were correspondingly underestimated.

Unmasking the Comet

No doubt Halley's scientific contemporaries regarded his prediction of the future transit of Venus as a highly interesting exhibition of astronomical knowledge, but as falling well within the province of one who had devoted much time to calculation of planetary orbits.

But the calculation of the orbit of a comet, coupled with the prediction that this visitor would return forty-three years later—in 1758—was something of a quite different order.

Of course, the comet did ultimately return, as the daring astronomer predicted, and was thus proved to be a member of

the planetary family—in future very properly to bear Halley's name. But something promised for the year 1758 was hardly likely to hush the voice of skepticism of the year 1715.

In any event, the feat of establishing a comet as a member of the sun's family is justly accounted one of the most spectacular accomplishments in the history of astronomy. It is difficult from this distance to realize adequately what such a pronouncement meant to the generation that heard it.

It must be understood that from the earliest times comets had been regarded, not as natural celestial bodies, but as supernatural phenomena. This was not merely popular and theological doctrine, but it was an estimate that only the most rationalistic of astronomers thought of challenging.

Doubtless a greater number of people had been terrorized by the appearance of comets than by the aggregate hordes of all the barbarians that had swept across Europe throughout the ages.

As a supernatural agent, the comet had credentials the most authentic. Says Andrew White:

"The belief that every comet is a ball of fire flung from the right hand of an angry God to warn the grovelling dwellers of earth was received into the early Church, transmitted through the Middle Ages to the Reformation period, and in its transmission was made all the more precious by supposed textual proofs from Scripture. The great fathers of the Church committed themselves unreservedly to it."

The names of Origen, Bede, St. Thomas Aquinas, and the sainted Albert the Great are cited, among others, as upholders of the doctrine that comets are "signs and wonders." They founded their opinion, of course upon scriptural texts.

There was even higher authority. The comet of 1456 ap-

peared at a time when the Turks were just making good their footing in Europe. The Pope of that period, Calixtus III, is said to have been so alarmed at the appearance of the celestial monster as to have "decreed several days of prayer for the averting of the wrath of God, that whatever calamity impended might be turned from the Christians and against the Turks."

"And that all might join daily in this petition, there was then established that midday Angelus which has ever since called good Catholics to prayer against the powers of evil. Then, too, was incorporated into a litany the plea, 'From the Turk and the comet, good Lord, deliver us.' "

That, to be sure, was long before the time of Halley. But the attitude of people in general and the Church in particular toward comets had not changed in the intervening period.

The citation of the Pope's comment is pertinent, because his particular comet was the same one which returned in 1682—and was then largely responsible for arousing the interest in its species of the young man who was subsequently to prove it an impostor.

Comets as Fire-Balls of Wrath

At this time, so fully did the comet maintain its prestige, that we find Ralph Thoresby, a Fellow of the Royal Society, calling on the Lord in his diary, "to fit us for whatever changes it may portend; for, though I am not ignorant that such meteors proceed from natural causes, yet are they frequently also the presages of imminent calamities."

And this was the caution of the man of science. The contemporary, Thomas Burnet, author of a famous "Sacred Theory of the Earth" (1681), that commanded attention for a hundred years thereafter (the writer a Royal Chaplain and a Cabinet officer), not only accepted in full the traditional status of the

comet as a fire-ball flung from the hand of God to menace man, but went a step farther, advancing the theory that comets are places of punishment for the damned—literal "flying Hells."

This author, incidentally, was a strict contemporary of Newton, who, to his death, rejected the Newtonian hypothesis. His selection of the comet as the locus of the important region hitherto supposed to be placed at the center of the earth, was perhaps influenced by his theory that the center of the earth is in fact a mass of water, a portion of which had burst through the shell of the earth—theretofore perfectly smooth and devoid of oceans—to constitute the celebrated Noachian flood.

He believed that existing mountains are fragments of the upheaved shell. And he argued not without plausibility that had there been seas prior to the flood, people would have learned to make boats to sail on them, and therefore would not have been destroyed so effectively by the Deluge.

William Whiston, Professor at Cambridge, in his new "Theory of the Earth," published ten years after the appearance of Newton's *Principia,* supplemented Burnet's theory of explaining that the deluge itself had been due to the impact of a comet's tail.

Both these conceptions found high favor in Germany. Witness Johann Gottsched, most noted critic of his day, who in a voluminous introduction to a treatise of one of his contemporaries, published in 1742, upholds the idea that the agency of comets in the Creation, the Flood, and the final destruction of the world is fully proved.

These are but incidental references to an inexhaustible literature, ecclesiastical and supposedly scientific, in which the unique

How Halley Challenged the Comet

position of the comet as a messenger of Divine wrath is exposited in detail or accepted as a matter of common knowledge.

And now came Halley, with a paper in which he first treats the orbits of comets as he would treat the orbits of any other planetary bodies, reaching a conclusion that in fact these orbits are not parabolic, as had been supposed, but are really elliptical, like the orbits of planets themselves, except that the ellipse is enormously elongated.

His second conclusion is that the comet of 1682, familiar to the contemporary world, is in reality the same comet that had appeared in 1607, in 1531, in 1456, and in 1305. The same comet to which Pope Calixtus paid attention, and which had acquired baleful notoriety on the other occasions to give it permanent remembrance.

This estimate was based in part on such records as were available of the appearance and apparent orbit of the comet on two or three of the earlier occasions; partly on the fact that the interval between the dates noted is in each case seventy-five or seventy-six years or twice that—the presumption being that records of the appearance of the year 1380 chanced not to have been preserved.

All this considered, Halley thinks that he has identified these successive apparitions as one and the same comet. And there follows his famous prediction:

"Hence I think I may venture to foretell, that it will return again in the year 1758. And, if it should then so return, we shall have no reason to doubt but the rest may return also: Therefore, Astronomers have a large field wherein to exercise themselves for many ages, before they will be able to know the number of these many and great bodies revolving about the

common Center of the Sun, and to reduce their Motions to certain Rules."

That prophecy marked the beginning of the end of the prestige of the comet as a fire-ball of Divine wrath. But of course the actual force of the argument was not felt until the prophecy was verified on Christmas day of the year 1758—sixteen years after the death of the prognosticator.

New Sights for Telescopes

Halley's chief fame as unmasker of comets was therefore posthumous. But his astronomical activities in other fields gave him the widest possible fame among his scientific comtemporaries, following up the early reputation gained by his mathematical calculations and his journeys to southern seas to test the variations of the compass.

The forward-looking quality of Halley's mind was shown, not only in his attitude toward the Newtonian hypothesis, but in his receptiveness to new ideas in general. Naturally he had the keenest interest in the new and improved astronomical instruments for which the epoch is distinguished.

A characteristic anecdote is told of his investigation of the question whether telescopic sights, recently introduced, were superior to the plain sights hitherto used by astronomers. It appeared that Johannes Hevelius, of Dantzic, reputed to be the most keen-eyed star-gazer of his generation (he gained fame by accurate description of the markings on the moon), declined to use the new sights.

Halley visited the veteran astronomer, in order that he might satisfy himself, by comparative observations, as to the relative merits of the old and new styles of sights.

Side by side, Hevelius and Halley made their observations, one with the old equipment, the other with the new. The results

showed slightly in the younger man's favor—but only slightly, for the skill and dexterity of the aged Hevelius almost compensated for the defects of the old method, to which he continued to cling to the time of his death in 1687.

Needless to say, all instrumental improvements were utilized by Halley in his own series of observations.

FIG. 42.—Johannes Hevelius (1611-1687). (Adapted from Bell's *The Telescope*. Original source not stated.)

Proper Motion of Stars

One result of the greater accuracy of observation made possible with improved telescope sights and micrometers was Halley's highly important discovery that at least three prominent stars appeared to have shifted their relative positions, in relation to neighboring stars, in the course of centuries, as tested by comparative study of ancient star-charts.

After making allowance for possible, even probable, inaccuracy

of observation of the early astronomers, Halley was satisfied that the seeming shift of position of the three stars was not thus to be accounted for.

He believed that what he observed was an actual or "proper" motion of the stars themselves.

The inference was valid, and the discovery of proper motion, announced in 1717, gave Halley secure position among the world's greatest observing astronomers.

The import of the discovery can with difficulty be realized today, when it is familiarly known that all stars are in motion. In the modern view, stasis would be the inexplicable anomaly. But up to the time when Halley made the observations that detected stellar movement, there had been no valid ground for suspicion that any star changes its relative position in the heavens.

The old Oriental description of the heavens as a solid firmament, "strong and as a molten mirror," supporting the upper waters, "that be above the heavens," may have been mentally challenged by some astronomers, but there was no shred of evidence to support their skepticism.

The entire sphere of the stars of course shifts slowly year by year, this uniform movement causing the precession of the equinoxes that Hipparchus discovered back in the old Greek days. But such a rotation is quite consistent with the conception of the entire sphere as a solid in which the stars are imbedded immovably.

Now that individual stars were seen to change their position among their fellows, this conception would be no longer tenable.

Here, then, was yet another new thing in the heavens—a new thing in that remote sphere of the firmament which, according to

the Oriental tradition as recorded in Genesis, was a more primordial structure than the earth and sun and planets.

That the stars which, apparently almost as an afterthought ("He made the stars also."), had been created and imbedded in the firmament, rather as ornaments than for any specified purpose unless it were to delight the eyes of man, should prove capable of leaving their heavenly matrix or shifting about in it, seemed astonishing almost beyond belief.

Would the impious telescopes of the astronomers leave nothing of the sacred celestial mechanism unchanged?

The answer ultimately to be given was that they would leave nothing.

The best that could be hoped for was that the champions of the ancient order might find consolation in recalling old Isaiah's prophecy that the heavens should "vanish away like smoke."

Not that the infinitesimal movement of three stars can be taken as a long step toward vanishment of the myriads now revealed by the telescope. But the possibility of movement of even a single member of the "eternal company" of the heavens must be considered an amazing and even terrifying portent.

Halley the Rational-ist

Halley died as he could have wished, painlessly, sitting at his telescope in the observatory. He was in his eighty-sixth year.

Perhaps no man of great activity ever stimulated his generation to more unanimous praise of his qualities of heart and mind. During a long life of almost unprecedented scientific and literary activity, he never became involved in a single controversy—in itself a record almost without example.

Says a biographer:

"He was rendered socially attractive by the unfailing gayety which embellished the more recondite qualities of a mind of

extraordinary penetration, compass, and power. He was disinterested and upright, and wholly free from rancor or jealousy."

Another biographer, speaking with equal enthusiasm of the great astronomer's "ardent and glowing temper—generous and friendly disposition, and great candor," adds:

"That he was with all his learning and amiable qualities an infidel in religious matters seems as generally allowed as it appears unaccountable."

Times change. Today it does not seem "unaccountable" that a man of intelligence should be a rationalist. But we learn without surprise that the greatest astronomer and one of the greatest scholars of his day was barred from the Savilian Professorship in Oxford in 1698 because of his skeptical attitude of mind toward Oriental traditions the acceptance of which by persons otherwise intelligent would seem "unaccountable" did we not know the power of tradition to befuddle the judgment.

Perhaps it is more significant that a few years later the Oxford position was open to Halley — though his attitude had not changed.

This suggests that the leaven of the Copernican and Newtonian conceptions was really working, even in the strongholds of conservatism.

Opposition Begins to Weaken

But, indeed, it is quite impossible that the unending series of new astronomical discoveries, all tending to support the Copernican doctrine and to evidence the illusory character of the Oriental conceptions, should fail to have some effect upon the still overwhelmingly dominant forces of the champions of the Oriental cosmology.

After all, little as their actions suggest it, the ecclesiastical authorities are not always deliberately and wilfully oblivious of

logical interpretation of the observed phenomena of nature. It is only that their preconceptions make them incapable of seeing the truth until it has been thrust before them again and again.

Then they begin to rub their eyes.

So we find that in the early 18th century evidences begin to be apparent of solicitude in the minds of some of the leaders as to whether there may not after all be a possibility—just a bare possibility—that the astronomers who have been bombarding the world for the past two centuries or so with new facts and theories born of their observations, may have discovered something of not altogether negligible importance.

Nothing that could by any possibility invalidate the slightest essential of the assured truth transmitted from Oriental antiquity of course. But conceivably something calling for interpretation.

In a word, it would appear that the solicitude of the more progressive thousandth of the ecclesiastical world was at least mildly aroused by the series of discoveries, all telling for the Copernican thesis.

A few were beginning to rub their eyes.

The calling of Halley to the Savilian professorship at Oxford, from which he had previously been barred, is an example. Here is another:

In 1722, five years before Newton's death, and while Halley was still in full activity, a sixth edition appeared of Thomas Burnet's famous work about the egg-shell earth that had been smashed by God's own hand to make the deluge when the actions of fallen man became intolerable to man's Creator. The work had a preface which made a remarkable concession. Thomas Burnet himself had died a few years before. We may infer, therefore, that the preface was written by someone of

the younger generation who, after the manner of members of younger generations, was disposed to look askance at the opinions of his elders.

At all events, this document comments on the oft-cited error of St. Augustine in opposing the round earth and the doctrine of the Antipodes. The great post-Nicene Father had vigorously denied the possibility that there could be inhabitants of the other side of the world, even if it were round, because the Apostles were recorded as having carried the Christian doctrine to all the peoples of the earth—and no Antipodeans were recorded to be among them.

Yet Columbus and Magellan, it was pointed out, had found Antipodeans actually living on the other side of the globe—flesh and blood human beings, not to be reasoned out of existence by even orthodox sophistry.

And so, says this annotator of the famous sacred theory of the earth, writing in the year 1722, not yet two centuries after the death of Copernicus:

Theory Versus Demonstration

"If within a few years or in the next generation it should prove as certain and demonstrable that the earth is moved, as it is now that there are antipodes, those that have been zealous against it, and engaged the Scripture in the controversy, would have the same reason to repent of their forwardness that St. Augustine would now, if he were still alive."

This after all is but a paraphrase of words pronounced a century earlier by that most astute of Jesuit Cardinals, Father Bellarmin:

"I say that if a real proof be found that the sun is fixed and does not revolve around the earth, but the earth around the sun, then it will be necessary very carefully to proceed to the explana-

tion of the passages of scripture which appear to be contrary, and we shall rather say that we have misunderstood these than pronounce that to be false which is Demonstrated."

It was Father Bellarmin, it may be recalled, who pronounced judgment against Galileo when he was first called before the authorities of the Inquisition—albeit there was nothing to suggest eye-rubbing in the condemnatory verdict he then hurled at the heretic.

Authority Versus "Demonstration"

The great Cardinal, counted the foremost theologian of his age, is credited with being "earnest, sincere, and learned." Nothing speaks louder for his sagacity than the sentence just quoted.

In common with his associates, he was doubtless altogether sincere in believing that the "pretended discoveries" of Copernicus and Galileo "vitiate the whole Christian plan of salvation," "cast suspicion on the doctrine of the incarnation," and "upset the whole basis of theology."

Doubtless he was fully in accord with the estimate of another contemporary who thus referred to the Copernican doctrine:

"If the earth is a planet, and only one among several planets, it cannot be that any such great things have been done specially for it as the Christian doctrine teaches. If there are other planets, since God makes nothing in vain, they must be inhabited; but how can their inhabitants be descended from Adam? How can they trace back their origin to Noah's ark? How can they have been redeemed by the Saviour?"

Obviously there can be but one answer to these questions, *if* the Copernican doctrine is true.

The answer implied, equally of course, is that the Copernican doctrine is *not* true.

Yet apparently the astute mind of the Cardinal could not altogether avoid a suspicion that the new doctrine *might* be true. And, good churchman though he was, he realized that even Oriental tradition (or as he would have phrased it, the word of God Himself) must be re-interpreted if found to conflict with an astronomical Demonstration that the earth and not the sun revolves.

Not for a moment would he concede that this had been demonstrated by Copernicus and Galileo. Nor can the modern critic gainsay this verdict. The revolution of the earth had not been *demonstrated* by Copernicus or Galileo. It was not demonstrated by Kepler, nor by Newton, nor by Halley.

But now there came a man who, six years after the appearance of Thomas Burnet's book of the equivocal preface, and one year after the death of Newton, was to furnish the long-awaited demonstration.

It was well for the peace of mind of Cardinal Bellarmin that he did not live to see that day. As for Bellarmin's successors, it was well for their peace of mind that for the most part they were heritors of the prejudice from which he was not free, and not of the earnestness, sincerity, and sagacity that gave him premonitory warning of the cogency and import of the new astronomical observations.

That we may get the full force of the story of the demonstration of the earth's revolution to be told in the ensuing chapter, let us put ourselves in the attitude of mind of the masses of mankind in Christendom at the time when this demonstration was made, by reflecting a moment on a pronouncement of one of Cardinal Bellarmin's contemporaries and fellow-Jesuits, Father Melchior Inchofer:

"The opinion of the earth's motion is of all heresies the most abominable, the most pernicious, the most scandalous. The immovability of the earth is thrice sacred; argument against the immortality of the soul, the existence of God, and the incarnation, should be tolerated sooner than an argument to prove that the earth moves."

Well and good.

But the man whose achievement is now to claim our attention did not come forward with an argument. He merely turned his eyes thoughtfully up to the starry firmament and reported what he saw.

He never dreamed that he should see there what he did see. Nor had he at first the slightest notion how to interpret the celestial vision.

XVI

JAMES BRADLEY—THE STARS NOD THEIR VERDICT

BEHOLD, then, a young amateur in astronomy, a clergyman by profession, going down on a certain memorable day into a cellar, and there seeing wonders of the firmament that no eye had ever seen before, nor any brain conceived.

The young man's name is James Bradley. The phrase "aberration of light," to be associated with his name throughout the future, is a phrase hitherto unknown, applied to a phenomenon hitherto unsuspected. The word "nutation," also associated with

the name of Bradley, is equally novel in its application to any astronomical phenomenon.

It is a rare experience for an amateur in science to have his name thus linked with celestial processes.

To be sure the young ecclesiastic, when he had ceased to be so young, was made Astronomer Royal of England, in succession to the immortal Halley. But the work that gave him distinction was performed while he was still an amateur.

It was in the year 1725 that this born star-gazer went from time to time into a cellar, looked up a chimney, and discovered that the world moves.

That sentence obviously needs expansion. Let me make clear the essentials of the story of which it is the summary.

At the outset, it will be understood of course that the chimney up which the young would-be astronomer directed his gaze, had a telescopic lens at its top and an objective at its bottom. In other words, the chimney supported the tube of a telescope. It was a relatively immobile telescope, adapted only for bringing light from a spot in the heavens very near the zenith.

A Strange Chimney View

For that purpose, however, the chimney answered very well. For it chanced that the object of the young astronomer—who had at first a joint worker in a friend, Molyneux by name, and incidentally the owner of the house—was to observe a particular star which was known to pass the meridian almost exactly at the zenith.

The intention was to discover whether or not this star changed its position in the heavens, as compared with neighboring stars, if viewed at different seasons—say at a six-months' interval, when the earth, if it actually pursues an orbit about the sun, will be at opposite sides of that orbit.

In a word, the object of the young star-gazers was to discover whether the star in question—a fairly bright star in the head of the constellation Draco—would reveal a measure of parallax.

The parallax of a star is an elusive something for which many astronomers before the time of Bradley had vainly sought.

There is much involved in the quest, for if it could be shown that stars have parallax, a practical demonstration would be given that the earth changes its position between one season and another, and therefore may confidently be believed to be circling in a wide orbit about the sun, in accordance with the Copernican doctrine.

If, on the other hand, stars have no parallax, how can we believe that the earth does make such a journey? For is it conceivable that any star could be so distant that a base line many millions of miles in length—the diameter of the earth's orbit—could fail to show any difference of angle in the line of sight of a star as viewed from its two ends?

A Star Change, But Not Parallax

Now the truth is that the stars *are* inconceivably distant, and only a few of them, even with the refined methods of our later time, show any parallax that can be measured.

Therefore it is not strange that all the astronomers who had made the search had failed.

But obviously this put weapons into the hands of the opponents of the Copernican system—the "Anti-Copernicans" as Bradley names them in a paper in which he describes his own discovery.

Incidentally, the fact that he does make such a reference gives added evidence (were such needed) that in 1725, when the chimney search was made, there were still active opponents of the heliocentric doctrine, already nearly two centuries old, abroad in the land.

But now for the odd denouement of the young clergyman's quest.

He did, indeed, find that the star (known as *Gamma* Draconis) shifted its position in the course of time. But the shift was not the kind of shift that was looked for.

If a star were to show parallax, its shift would naturally be in the direction of the axis of the earth's ellipse of rotation. Gamma Draconis, as viewed through the chimney, shifted in the direction of the earth's flight—tangentially to the orbit instead of transversely.

What could this mean? Neither young Bradley himself nor anyone else had the slightest notion.

It was an anomaly that required further investigation.

No greater surprise, probably, was ever sprung on a watcher of the stars than that which greeted the eyes of the young ecclesiastic and his associate when near midday of December 17th, 1725, it was discovered that their focal star had passed a little more southerly in the sky this day than it had previously been observed to cross.

To be quite accurate, it should be said that the surprise came three days later, when the star was again tested, and found to pass still further to the south. For now the observers were certain that they were witnessing an actual phenomenon—instead of making a mistaken observation, as they had at first feared.

Further observations in succeeding months confirmed this belief.

And the belief became a certainty when by the middle of April the star appeared to be returning again towards the mark, until

finally about the beginning of June it passed at the same distance from the zenith as in December, when first observed.

Other Stars Partake of the Same Motion

The next step was to build a new observatory, at Bradley's own home, in order that other stars might be observed.

Needless to say, the new telescope was not placed in a chimney, and therefore had greater flexibility of action. Not less than twelve bright stars were fixed on that could be observed throughout the year—stars bright enough to be seen telescopically in the daytime, when nearest the sun.

New developments followed that need not be rehearsed. But the upshot was that the original observation was confirmed.

It was found that all stars observed under certain conditions performed the same curious oscillations, backward and forward, that had been first revealed by the anomalous action of Gamma Draconis. Stars near the pole describe a circle; those in middle latitude, an ellipse; those near the ecliptic shift back and forth in a right line. The amount of radial displacement is everywhere the same—about 20 seconds of arc.

At first the young astronomer thought that this shifting of the stars might be due to a nutation, or nodding, of the earth's axis.

He presently convinced himself that this could not be the correct explanation. He next surmised an alteration in the direction of the plumb-line, with which the line of sight of the telescope was constantly rectified. But this upon trial proved insufficient.

Then refraction was taken into account. But here also nothing explanatory could be detected. Near the zenith, refraction is negligible, and for other stars movement remained after all due allowance was made for the atmospheric effect.

And then, in the strangest way, came the revelation as to the true explanation of the fantastic phenomenon.

It came about in this wise. The young clergyman had gone for a sail on the Thames, and as the boat shifted position, he noted that the little flag that served as wind-gauge altered its position from time to time, obviously not indicating correctly the direction of the wind.

A Sailboat Gives the Clue

He called the attention of one of the sailors to this anomaly, and was told that what he observed was due to the fact that the flag showed, not the direction of the wind merely, but the combined influence of the wind and the motion of the sailing vessel itself.

Further observation convinced young Bradley that this explanation was quite valid.

That set him thinking.

Presently another and more familiar experience came to his attention. If, when the rain is falling straight down, you walk forward rapidly carrying an umbrella directly above your head, the rain strikes aslant under the umbrella against your body or into your face.

To shield yourself you must hold the umbrella forward—more acutely forward in proportion to the speed of your own movement.

Here, then, was another illustration of a moving something coming against another moving something, with apparently altered direction of impact.

The Explanation of Aberration

Then came the application. Light is a something which moves through space at less than infinite speed. Roemer had proved that in the preceding century, though his evidence had not been generally accepted. The earth is a something which moves

through space at great speed—if the Copernican doctrine is true.

Why is not the case of light and the earth strictly comparable to that of the wind and the ship or of the rain and the umbrella?

To Bradley it seemed that the cases were strictly comparable.

He had found the solution of his problem and incidentally had proved that Copernicus and Roemer were right. The strange shift of position of the stars, first in one direction and then in the other, was due to the progressive motion of light and the earth's annual motion in its orbit.

"For I perceived that, if light was propagated in time, the apparent place of a fixed object would not be the same when the eye is at rest, as when it is moving in any other direction than that of the line passing through the eye and object; and that when the eye is moving in different direction the apparent place of the object would be different."

That was the true answer; and the phenomenon passed into history as the aberration of light—a major discovery made by a young astronomical amateur at the outset of his career.

A long life of astronomical research was to follow in the course of which Bradley not only made one other fundamental discovery, but piled up an enormous number of observations as to the exact positions of stars, which were to be of inestimable service to later generations of astronomers.

Eighteen Years to Prove Nutation

The discovery of nutation, that is to say, of the earth's nodding motion was in a sense a sequel to the aberration observation. Nutation is an infinitesimal wabble which the earth's axis makes, to give a wavering effect to the vast circling sweep that carries the axis full circle in about twenty-six thousand years.

This minor wabble is due to the moon's action on the earth's

protuberant equatorial region. It constitutes a little wavy curve, of 1400 indentations in the entire circumference, or one indentation for each period of something less than 19 years.

As the earth nods, of course, the stars seem to shift their positions. The shift is infinitesimal, yet appreciable to the eye of so keen an observer as the discoverer of aberration. As the earth recovers from its nod, the stars naturally shift back to their original positions.

The observer must wait more than eighteen years to make sure of this return—that his theory may be adequately tested.

Bradley did wait eighteen years before he made the announcements of his discovery.

Before the end of the year 1728 he had records of a hundred observations on a single star, and could speak of "the equation for the nutation."

But the letter on which he announced his discovery bore date of December 31st, 1747.

Such is the scientific caution which, coupled with pertinacity of effort, leads to valid discovery.

Further Studies of Proper Motion

In the letter that announces the discovery, Bradley makes further discussion of the possible motions of the stars.

He suggests a method for discovery of the cause of the apparent change in the obliquity of the ecliptic, if the mean obliquity be found to diminish gradually. He makes the further suggestion that if dependence can be placed on the observations of earlier astronomers, there appears to have been a real change in the position of some of the fixed stars with respect to each other—a change that seems independent of any motion in our own system, and can only be referred to some motion in the stars themselves.

He cites Arcturus as affording strong proof of this.

He has found that the present declination of that star is more divergent from its place as determined either by Tycho or Flamsteed than can be suspected to arise from the uncertainty of their observations.

About 30 years earlier, Halley (as we have seen) had made observation of the shifted positions of certain of the stars, as determined by comparison with the records of Zimocharis and Aristyllus, near 300 B. C., and by Hipparchus about 170 years after them; that is about 130 B. C. He had concluded that the fixed stars in 1800 years will advance somewhat more than 25 degrees in longitude, or that the precession is somewhat more than 50 seconds per annum. But to his great surprise he found that the latitude of three of the principal stars in the heavens directly contradicted the supposed greater obliquity of the ecliptic, which seemed confirmed by the latitudes of most of the rest.

He had spoken then of the particular motions of these stars.

Now Halley's successor as Astronomer Royal confirmed the observation of his great predecessor.

As to both series of observations, their authors spoke with reserve, because of the uncertainty as to the degree of error that must attach to observations made in the pre-telescopic days. Yet both men were firmly convinced that actual shifts of positions of some of the brighter, and therefore presumably nearer, stars had been observed.

So now it might be said to be fairly established that the "fixed" stars have actual motion.

Interpretation of the meaning of the observed shift of a few fixed stars was reserved for another amateur observer, this time

a musician, who was already in the world, though not yet of an age to think about telescopes in the year 1747, when Bradley's letter was written.

I refer, of course, to Frederick William Herschel, about whom we shall hear much more in due course.

Meantime in leaving the young clerical who became Astronomer Royal—attaining a place, in the words of Delambre "among the most distinguished after Hipparchus and Kepler, and above the greatest astronomers of all the ages and all countries"—let us revert for a moment to the discovery of aberration, and its meaning for the cosmologist.

What Aberration Proves

Taken together with the allied discovery of nutation, the amazing observation of the shift of the stars through aberration constitutes the first really demonstrative proof of the actuality of that orbital motion of the earth about the sun which is the prime essential of the Copernican doctrine.

Here is a phenomenon, involving all visible stars, which is simply and convincingly explained on the supposition that the earth is moving swiftly through space; but which becomes utterly fantastic and inexplicable if we assume that the earth is stationary.

It was a demonstration, to be sure, the force of which could be fully realized only by astronomers. But it could leave no doubt in the mind of any competent star-gazer. And so soon as the phenomena of aberration and nutation were accepted as actualities, there could be no further question by any one competent to weigh astronomical evidence that the Copernican scheme of the solar system is also an actuality.

It would have been a strangely gifted astrologer that could have forecast such a sequel for the act of the young clergyman

who once on a time went into a cellar and scanned the sky through a chimney.

Elusive Parallax

It will be recalled that Bradley's first observation of a star was made with the design to discover whether the star showed "parallax."

But Bradley, as we know, did not determine the parallax of his star. With the instrumental aid then available, it was quite impossible that he should have determined it. The star-movement that he did observe, which led to his wonderful discovery of the aberration of light, was backward and forward oscillation across an arc of about forty seconds—and this, as was found out later, is more than 50 times the parallax of any star.

Bradley's great genius was shown, not so much in observing the movement of the star, on the relatively large scale of aberration, but in first noting that other stars partake of the same motion, and then finding a valid explanation for the phenomenon.

Bradley reported, however, that he felt very confident that his instruments would have revealed to him a parallactic shift of one second of arc, had it existed, in the case of any one of the great number of stars that he ultimately charted with meticulous accuracy.

He even felt rather confident that he should have noted a parallactic shift of half a second of arc.

The Stars Are Enormously Distant

Therefore he felt certain, and so stated, that no star of all those that he charted can be less distant from us than 400,000 times the distance of the sun.

That means, if you state it in words, more than thirty-six trillion miles. In figures 36,800,000,000,000 miles.

It appears, then, that the negative results of Bradley's star-tests were hardly less interesting than the positive result. The

measurements which directly proved the motions of the earth indirectly proved the quite inconceivable remoteness of the stars.

The sun's distance is almost inconceivably great. No one can clearly grasp the idea of 92,000,000 miles. But one can realize that the eight figures thus placed in a row represent a very great distance indeed.

And when we are told that, using this distance as a unit yard-stick, and applying 400,000 such yard-sticks, we do not reach the nearest star—well, at least imagination gets a fillip.

Common sense tells one that a body which shines at a bright light at such a distance must be enormously big and bright; and that a vast galaxy of such bodies at such a distance does not swing full circle in twenty-four hours, with the earth or anything else for the center of revolution.

Whatever way you look at James Bradley's star-measurements, then, you get the same answer. The earth revolves round the sun, and spins on its own axis. The stars do not revolve about either earth or sun.

And the bewildering thought presents itself that bodies which shine so brightly when more than 400,000 times the sun's distance, might prove to be comparable to the sun itself in size and intrinsic brightness, if you could get nearer them.

Could it be, then, that the stars of the firmament—those minute twinkling lights which, according to the authoritative record, were created casually, as it were by afterthought, to enjewel the firmament — are in reality suns, comparable to *the sun?*

A staggering thought.

Absolutely alien, no doubt, to the average mind at the middle of the 18th century. Yet a thought that proved highly stimulative

to an exceptional mind here and there among the contemporaries of the discoverer of Aberration—as we shall see presently.

Bradley died in 1762—thirty-seven years after his demonstration that the world does move.

Contemporary judgment epitaphed him as: "Humane, benevolent, and kind; a dutiful son, an indulgent husband, a tender father, a steadfast friend."

The fullness of his scientific accomplishment was matched by the modesty, generosity, and blamelessness of his private life.

A great astronomer, and a great man.

Retrospect and Prospect

And now one might suppose the Copernican theory to be at last firmly established.

Copernicus had died in 1543. At the time of Bradley's death, 219 years had elapsed. Not until the year 1946 shall we of the modern world be as far removed from the date of Newton's death as the world then was from the death of the originator of the heliocentric doctrine,—the discoverer of the truth that the sun is the center of our planetary system.

Surely two centuries must have accomplished something for the advancement of astronomical truth.

But let us try to gain a correct historical perspective.

It was three years after Bradley's death, and a full half-century after the *demonstration* that the world moves, that the French astronomer Lalande made the unsuccessful effort at Rome to have the work of Galileo removed from the *Index*.

Galileo by now was a century and a quarter dead, and his fame had spread throughout the scientific world. Already he ranked among the immortals, to be known throughout the future as the greatest man of science that Italy ever produced. But his

name was still anathema among the authoritative upholders of the old astronomical traditions.

Not yet by any means was the great Italian's *"E pur si muove"* heard or heeded in the land of his birth.

And at the north of the Alps, in the native lands of Luther and Calvin, affairs were not far different.

Luther and Calvin themselves, of course, together with Melancthon and Zwingli and John Knox and other leaders of their period had been as firm upholders of the Oriental cosmology as the Italian authorities against whom they had rebelled.

Their successors had not changed.

John Wesley in England, the founder of Methodism, was a younger contemporary of Bradley. He lived till 1791, earnestly charging that the new astronomical doctrines "tend toward infidelity," and incidentally speaking more pregnant words than he knew when he declared that "unless witchcraft is true, nothing in the Bible is true," and that "the giving up of witchcraft is in effect the giving up of the Bible."

Out of the mouths of babes!

Of the same period and mind was John Hutchinson, professor at Cambridge, whose work in which the Newtonian theory was denounced as "atheistic" had wide currency, along with similar verdicts of Samuel Pike, Bishop Horseley and President Forbes.

The followers of Dr. John Owen, the Puritan, had by no means receded from his declaration that the Copernican system is "a delusive and arbitrary hypothesis, contrary to Scripture."

And in France, nine years before the death of Bradley the Court Physician Jean Astruc set the world agog by discovering, after years of learned investigation (what any unhampered boy of eight can discover for himself in five minutes) that two

accounts, mutually contradictory, of the origin of the cosmos are given in the first two chapters of the Oriental anthology which was the basis of all the opposition to the acceptance of the Copernican system.

It was something, to be sure, that this physician, himself a devout orthodox Catholic, should discover and reveal a discrepancy which, though clear as day, had apparently escaped detection of all generations of his predecessors. But we must understand that the innovator, though known in after time as the first exponent of the "higher criticism," was in his own day sneered at by theologians of all creeds as "a Doctor of Medicine who had blundered beyond his province," and "bitterly denounced as a heretic" throughout Europe.

Yet Astruc himself had not for a moment meant to challenge the old cosmology.

He had only desired to reassert the authorship of Moses against the argument of Spinoza.

In denouncing the impiety of the physician who discovered the obvious, champions of the Oriental cosmology of all complexions of faith were at one. And why should they not be? They had at no time differed as to the verbal inspiration and plenary authority of every syllable of the story of cosmology which was the sole source of information available.

It was Calvin in particular who had pointed to the 93rd Psalm, with its declaration that "the world also is established, that it cannot be moved," and asked contemptuously:

"Who will venture to place the authority of Copernicus above that of the Holy Spirit?"

The question seemed just as cogent, the argument as unan-

Plate X: JAMES BRADLEY (1693-1762)
(Crow-quill interpretation of the engraving in the volume of Bradley's *Miscellaneous Works*, Oxford, 1832)

swerable, to the authorities of the time of Bradley as in any earlier generation.

Could the reasoning of a Newton, the telescope of a Bradley, be admitted to belie the inspired words which expressly declare the earth to be immovable, and no less explicitly state that the sun does move?

Not yet.

But the fact that all the stars of the firmament nod approval of the Copernican doctrine could not be forever ignored, even though their testimony contradicts the record of the most highly prized of Oriental anthologies.

The discrepancy between star-record and book-record was in due course to cause much rubbing of eyes.

XVII

WRIGHT—LAMBERT—MASKELYNE—FROM MILKY WAY TO EARTH-CORE

STAR-CHARTS have great practical significance for the Astronomers Royal of England, and their confrères of other nations, whose official duties (since the time of Maskelyne, Bradley's successor) include the making of Nautical Almanacs, without which navigation of the seas would be a hazardous venture.

Celestial maps may interest in another way men who are not themselves professional star-gazers. And it may chance on occasion, that one of these amateurs is led to speculate about the star-

maps in a way the caution of the experts themselves would prevent them from speculating.

This is only another way of saying that some men are prone to observe, and to hold rigidly to what seem necessary deductions from their observations, and that other men are born generalizers.

Bradley, as we have seen, was one of the keenest observers that ever looked through a telescope. He was also an exceedingly sagacious reasoner. But he never jumped to conclusions. Nor had he the slightest propensity to invent, Kepler-like, geometrical or other phantasies to explain puzzling things that he saw. He waited four years after he had observed the oscillations of the stars, before he announced what he had seen, because he could not find a logical explanation of the curious phenomena.

When he did find an explanation, it was the right one. Moreover, his measurements were so accurate that the "constant of aberration" he determined has been but little modified by more recent observers, notwithstanding the improvements in instruments of precision. Similarly, Bradley waited almost nineteen years before officially announcing his discovery of nutation, though there could be no question in his own mind as to the nature of the phenomenon, and though he had told of his discovery in private conversations, years before the public announcement.

A man of that temper of mind will not rush into print with generalizations on any subject unsupported by evidence of the most clinching character. And Bradley in particular was disinclined to be dragged into print—let alone rushing—at any time or on any subject. Few men who accomplished so much have written so little. The records of Bradley's observations are voluminous; his comments on them are terse to the last degree.

So it is not strange that there is no record as to what this famous observer thought the probable character of the stars might be, or the mechanism of the heavens toward which his telescopes were directed.

This is regrettable, for surely a man who said so little must have reflected much. And a man of such logicality of mind must have drawn inferences from his observations that would have peculiar interest and importance.

Be that as it may, it was left for others to attempt to interpret his observations, coupled with observations of the other notable star-gazers, in terms of celestial mechanics. And there were at least three contemporaries of Bradley who made such attempts, with results that posterity has accounted altogether notable.

The Grindstone Theory of the Universe

The first of these was a physician of Durham, England, who bore the name of Thomas Wright.

Dr. Wright put forward his "Original Theory of the Universe," in the year 1750.

His theory was that the stellar system is shaped like a grindstone, and that the seeming superabundance of stars in the Milky Way is an optical effect, due to the fact that in looking into the Milky Way, circled about the heavens, we are looking toward the edge of the grindstone from a somewhat central position.

This conception, adopted and popularized subsequently by Sir William Herschel, came to be known as the "grindstone" hypothesis, and it is substantially a conception adopted by astronomers of our own day, as it was accepted by astronomers of the intervening generations.

In other words, the Durham physician put forward the first solution of the mystery of the galactic system ever suggested,

and guessed so well that succeeding generations could neither dispute it nor add anything essential to it. At least, not prior to the year 1930.

The words in which the pronouncement was made were doubtless thought simple in an age given to euphuism, but to the modern ear they sound befittingly pompous as becomes so oracular a message.

Wishing to say that the Milky Way is made up of many stars, he says it thus:

"This is the great Order of Nature which I shall now endeavour to prove, and thereby solve the Phaenomena of the *Via Lactea;* and in order thereto, I want nothing to be granted but what may easily be allowed, namely, that the Milky Way is formed of an infinite Number of small Stars."

Wishing, then, to describe the grindstone shape of the universe, as he conceives it, he conceals the idea with his code:

"Let us imagine a vast infinite Gulph, or Medium, every Way extended like a Plane, and enclosed between two Surfaces, nearly even on both Sides, but of such a Depth or Thickness as to occupy a Space equal to the double Radius, or Diameter of the visible Creation, that is to take in one of the smallest Stars each Way, from the middle Station, perpendicular to the Plane's Direction, and, as near as possible, according to our Ideas of their true Distance."

Having with the aid of a diagram made it increasingly difficult to understand that he merely means that the stars are scattered everywhere more or less evenly, but seem thicker along the Milky Way because we see more of them there, he desires to express the further thought that the stars are all in motion. He goes on "to apply this Hypothesis to our present Purpose, and

reconcile it to our Ideas of a circular Creation, and the known Laws of orbicular Motion, so as to make the Beauty and Harmony of the Whole consistent with the visible Order of its Parts."

To do this we are further assured, "our Reason must now have recourse to the Analogy of Things." And since analogy tells us that we must either move in right lines or in curves, we must assume that they either circulate in orbits somewhat in the same plane, like planets, or else in different directions as comets to round the sun.

Leaving his audience to choose for themselves between these hypotheses, the expositor branches to the consideration of the rings of Saturn, which he sagaciously interprets as made up of an infinite number of small bodies. All in all, it would be difficult to find words better adapted to conceal an idea than the words of this epochal paper in which the grindstone theory of the universe is presented. Nevertheless, the idea is there, and the document stands as a monumental contribution to cosmologic speculation.

Among other things, it showed that here at the middle of the 18th century there were rationalists abroad who were unawed by the contemporary judgment that Newton by his statement of the law of gravitation had "substituted gravitation for providence," and had "taken from God that direct action on his works so constantly ascribed to him in Scripture and transferred it to material mechanism."

Obscurities of the wording did not disguise the fact that Thomas Wright was thinking explicitly in terms of "material mechanism." Perhaps he felt it wise to put a smoke screen of words about his daring conception — though not thinking it

necessary, as Huygens had done in announcing his hypothesis of the rings of Saturn a century earlier, to use an out and out cryptogram.

The Systems of Lambert

Meantime over on the continent there was an Alsatian who was thinking along similar lines, and who eleven years later, in 1761, expressed his conclusions as to the nature of the universe in terms as notable for clearness and precision as the other expositor's were for turgid obscurity.

The author of this system of cosmology is Johann Heinrich Lambert. His name suggests German origin, but he wrote in French. His treatment of the scheme of the universe might be described as "modern" and up-to-date, from the 20th century standpoint.

It is an "enquiry concerning the motion of the fixed stars," based partly on "the apparent as well as real light and magnitude of the stars," and partly on "the laws of cosmogony."

It is noted that the stars appear to casual inspection as if they were fixed in the same vaulted surface, but that this is an optical illusion. In reality, the stars are at very different distances, "as well as from the sun, which is the fixed star of our system."

It is noted that the stars become progressively more numerous with decreasing magnitude, and this comment follows:

"It is certain that this progression is much better accounted for by the different distances of the stars, though we are far from contending that they are all equally large and equally luminous."

Lambert declares that the number of stars in the Milky Way, compared with those without it, is like the ocean compared to a drop of water. The explanation is that the Milky Way lies in

the background of the other stars, at such an immense distance as prevents our discovering its component stars otherwise than with a telescope.

"This being the case no reason can possibly be assigned, why those stars should not be in themselves equally large and luminous with our Sun." Furthermore "everything concurs to persuade us, that there is a distance between them similar to what exists between the other fixed stars; for example, between the Sun and Sirius, or the fixed star the most contiguous to our system."

It follows that we must assume that the stars of the Milky Way are arranged not in the same line, "but the one behind the other in immense serieses."

The whole system of visible stars is declared not to exhibit a spherical figure "but rather that of a physical plane or disk, whose diameter is much greater than the axis which measures its thickness. In this plane lie the Milky Way, and all that is without it. It represents a flattened cylinder, or a spheroid, which for a row of a hundred stars in its thickness, ought to have a train of millions in its length."

Here obviously, we have Dr. Wright's grindstone—virtually the same conception of the galactic system that had come to the English cosmologist.

It was then stated that the sun is not at the center of his system of fixed stars, the opinion being expressed that the center is either in the region of Orion or Sirius. As to the exact location, 20th century astronomers are not fully agreed. But they do agree with Lambert that the sun is not at the center.

They are inclined, too, to agree with Lambert's further contention that the galactic system is by no means the entire uni-

verse. A cautious modern would perhaps hesitate to express the plan of the universe quite as explicitly as Lambert expresses it. Yet how essentially "modern" is the picture presented by the Alsatian cosmologist's summary:

"The Milky Way comprehends several systems of fixed stars; those that appear out of the tract of the milky way form but one system which is our own. The sun, being of the number of fixed stars, revolves round a centre like the rest. Each system has its centre, and several systems taken together have a common centre. Assemblages of their assemblages have likewise theirs. In fine, there is a universal centre for the whole world round which all things revolve."

When such words can be written, the world has traveled far from the shell-like firmament of the old cosmology.

But let us not forget that no one would dare to put forward such a scheme as this, even as an hypothesis, who had not broken absolutely with authority.

The Cosmos of Kant

The third proponent of a new scheme of cosmology, and by far the most famous of the three, was Immanuel Kant, then Professor in the University of Königsberg, Germany.

In presenting excerpts from Kant's "Universal Natural History and Theory of the Heavens" of 1755, Shapley and Howarth make this comment on Kant, as a pioneer in the interpretation of the sidereal universe:

"He proposed many of the hypotheses which have been but recently restated or demonstrated, including the island universe interpretation of spiral nebulae, the displacement of the Sun to the north of the plane of the Milky Way, and the slowing down of the Earth's rotation through tidal friction arising from the Moon's attraction. His most significant contribution was the

speculation on the origin of the planetary system—a nebular hypothesis that preceded the better known Laplacian theory by forty years."

We shall learn something more of Kant's nebular hypothesis, in connection with Laplace's independent development of a sim-

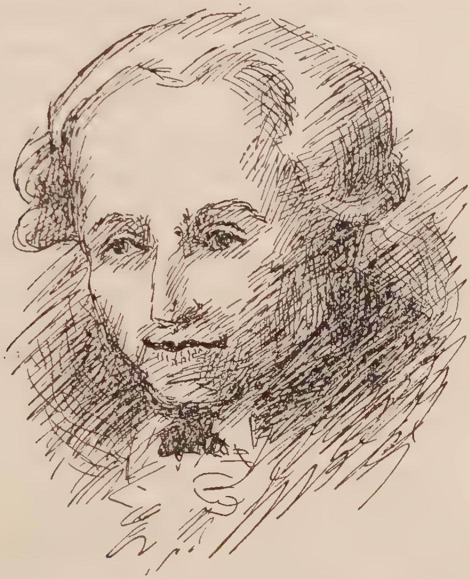

FIG. 43.—Immanuel Kant (1724-1804). (Adapted from familiar portrait of untraced origin.)

ilar hypothesis, in a later chapter. Here I wish merely to refer to the conception of the new universe which presented itself to the profoundest thinker of the 18th century—a conception necessarily based on the astronomical findings of star-gazers of the immediately preceding or contemporary generations.

Here, as with Wright and Lambert, we have the conception of a Milky Way of elliptical figure, but the perfectly definite conception is attained that our galactic system is only one of a

multitude of such systems—the nebulae being presented as "systems of many stars, whose distance presents them in such a narrow space that the light which is individually imperceptible from each of them, reaches us, on account of their immense multitude, in a uniform pale glimmer."

Contemplating the nebulae as outlying "island universes," Kant further conjectures that these "higher universes are not without relation to one another, and that by their mutual relationship they constitute again a still more immense system."

And the mind of the philosopher expands to this magnificent culmination:

"If the grandeur of a planetary world in which the earth, as a grain of sand, is scarcely perceived, fills the understanding with wonder; with what astonishment are we transported when we behold the infinite multitude of worlds and systems which fill the extension of the Milky Way.

"But how is this astonishment increased, when we become aware of the fact that all these immense orders of star-worlds again form but one of a number whose termination we do not know, and which perhaps, like the former, is a system inconceivably vast—and yet again but one member in a new combination of numbers! We see the first members of a progressive relationship of worlds and systems; and the first part of this infinite progression enables us already to recognize what must be conjectured of the whole.

"There is here no end but an abyss of a real immensity, in presence of which all the capability of human conception sinks exhausted, although it is supported by the aid of the science of number.

"The Wisdom, the Goodness, the Power which have been revealed is infinite; and in the very same proportion are they fruitful and active. The plan of their revelation must therefore, like themselves, be infinite and without bounds."

That such words would be spoken in the year 1755 may be taken as an index of the gigantic strides that had been made, thanks very largely to the star-gazers, since the time when Kant's great forerunner of the 17th century, Descartes, had lived in terror of authority, and for the most part had maintained silence regarding his own cosmogonic speculations, intimations of which are half-revealed in the famous theory of Vortices.

The bombardment of facts has been not without effect. A background of public opinion is being built up that will presently be recognized as a barrier against further extension of the antique conception. But to pursue that thought would lead to historical misconception. Let us correct the focus:

The decade that saw the presentation of the new cosmologies of Wright, Lambert, and Kant was almost exactly as far removed from the publication-time of Newton's *Principia* as the fourth decade of our own century is from the date of publication of Darwin's *Origin of Species.*

The implications of the Newtonian doctrine were no more acceptable to champions of the old cosmology in that decade of the 18th century, than the ultimate implications of the Darwinian doctrine are acceptable to the champions of the old theogeny in this corresponding period of the 20th century.

Maskelyne Weighs a Mountain

But now the Newtonian doctrine, already of course accepted by the leaders (if not by the drivers) at last was to receive support of unexpected kind, calculated to appeal to the man in the street. A curious demonstration of the truth of the law of

gravitation, as it operates here on the globe, was to be made by a man who followed Bradley's successor (N. Bliss) in the position of Astronomer Royal of England.

FIG. 44.—Nevil Maskelyne (1732-1811). (Adapted from Poor's *Nautical Science*. Origin not traced.)

The astronomer's name was Nevil Maskelyne. The record of his demonstration makes a rather curious story.

In the preceding chapter we saw a future Astronomer Royal pointing his telescope at a star, and thereby making final demon-

stration of the truth of the Copernican doctrine. Now we are to see his successor, by not dissimilar measurement of a star's position, doing a like service for the Newtonian doctrine, and

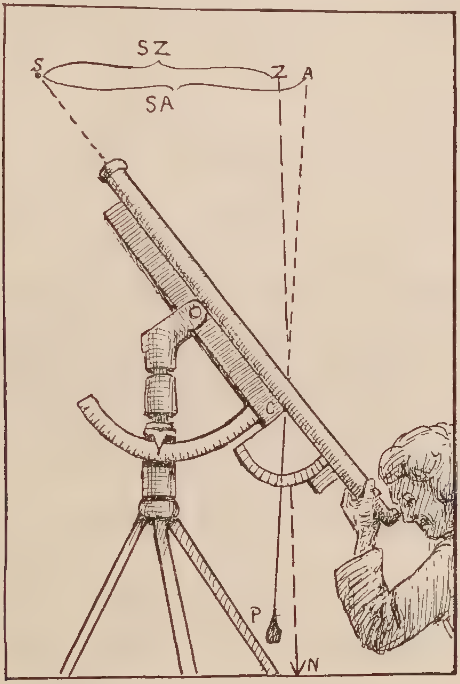

FIG. 45.—How Maskelyne Weighed the Mountain. (The plumb line is deflected toward the mountain so that the apparent zenith shifts to A, and the star's zenith-distance appears to be SA instead of SZ. On the other side of the mountain the apparent shift is in the opposite direction.)

at the same time striking a hard, even if indirect, blow at the old cosmogony by proving that the interior of the earth is quite different from the watery mass or hollow pit in which alternate terms the ancient descriptions were held to depict it.

So there is interest beyond what appears on the surface in the

fact that, in the year 1774, the Astronomer Royal of England set out to weigh a mountain.

Weighing a mountain certainly seems an odd task for an astronomer. Yet in effect that is what Maskelyne did. More technically, he tested the gravitation-pull of the mountain. But the thing seems less peculiar when we are told that what was ultimately accomplished was the virtual weighing of the earth.

What was specifically tested was the deflection of the plumb-line on either side of an abruptly rising "hog-back" mountain, testing the plumb-line in turn by the apparent deviation from the zenith of a star when viewed telescopically from opposite sides of the mountain. The Astronomer Royal knew that the star had not changed its position. What had really changed was the apparent zenith, as pointed out by the plumb-line. The apparent deviation showed how far the plummet (of known weight) had been pulled aside by the mountain.

A relatively simple application of the law of inverse squares (gravitation), with size and distance of mountain *versus* size and distance (to center) of earth for factors, revealed the relative density of earth-substance as a whole *versus* mountain-substance.

Result: The substance of the interior of the earth is about twice as dense as the substance of the crust—confirming by experiment a sagacious guess made almost a century earlier by Newton himself.

An incidental result was to give the quietus to Thomas Burnet's theory, still popular in 1774 when the mountain-weighing was done, that the interior of the earth is an abysm of water. It was now known to have more than five times the density of water.

Subsequent investigations were to lead to the conclusion that

the core of the earth is in reality chiefly composed of iron. But the purpose of the Astronomer Royal was fully accomplished when he had demonstrated that the earth could be weighed by his mountain and plumb-line method.

XVIII

HERSCHEL EXPANDS THE UNIVERSE

AT THE very time when the Astronomer Royal of England was weighing his mountain, and thereby giving new support to the Copernican and Newtonian doctrines, another man in England was preparing to make a most amazing series of demonstrations of the same truths, by turning his eyes zenith-ward with a quite different instrument.

The name of this new innovator was William Herschel.

He was thirty-six years of age when Maskelyne weighed his mountain, and known only to a very narrow audience as an excellent player of the oboe in a professional orchestra.

Ten years later the ex-oboe-player was the most talked about man in England, perhaps in the world, even in the day of Pitt and Fox, of Gibbon, Adam Smith, and Boswell's Dr. Johnson—not to mention Washington and Franklin.

The man who thus kaleidoscopically changed his affairs with the aid of a telescope was a Hanoverian by birth. But Hanoverians could hardly be counted as aliens in the England of the Georges. And in any event, William Herschel was soon wholly England's

by adoption—though Germany never ceased to claim a share in his glory.

In the best sense of the word, Herschel was a self-made man. Genius such as his is of course a heritage, yet there was nothing in his ancestry obviously to account for the spectacular success of the middle-aged musician who became first an amateur star-gazer, and then far and away the most successful observing astronomer of his own or any other age.

A Maker of Reflecting Telescopes

But Herschel was much more than a marvelous observer. He had extraordinary mechanical genius to begin with, and prepared for his future success by inventing methods of grinding blocks of metal into parabolic speculums. These, when silvered, constituted the reflected mirrors of telescopes of the type invented by Newton and perhaps independently by the French sculptor Sieur Guillaume Cassegrain, about the year 1672, but never put to conspicuous practical use in the intervening century.

To Herschel it seemed that this type of telescope offered possibilities not open to the ordinary telescope, the glass lenses of which were restricted in that day to a few inches in diameter. Herschel presently was able to make his reflecting mirrors many times the size of the largest lens hitherto ground.

His ultimate masterpiece was a 48-inch mirror, with focal length of 40 feet—mounted on a great outdoor scaffolding, where the observer perched fifty feet in the air. This was the father of all modern great reflecting telescopes, and in its day it was regarded as an eighth wonder of the world.

Herschel's first fame, however, was achieved with an instrument of far more modest dimensions. The discovery of the new comet which turned out to be a wonderful new world was made

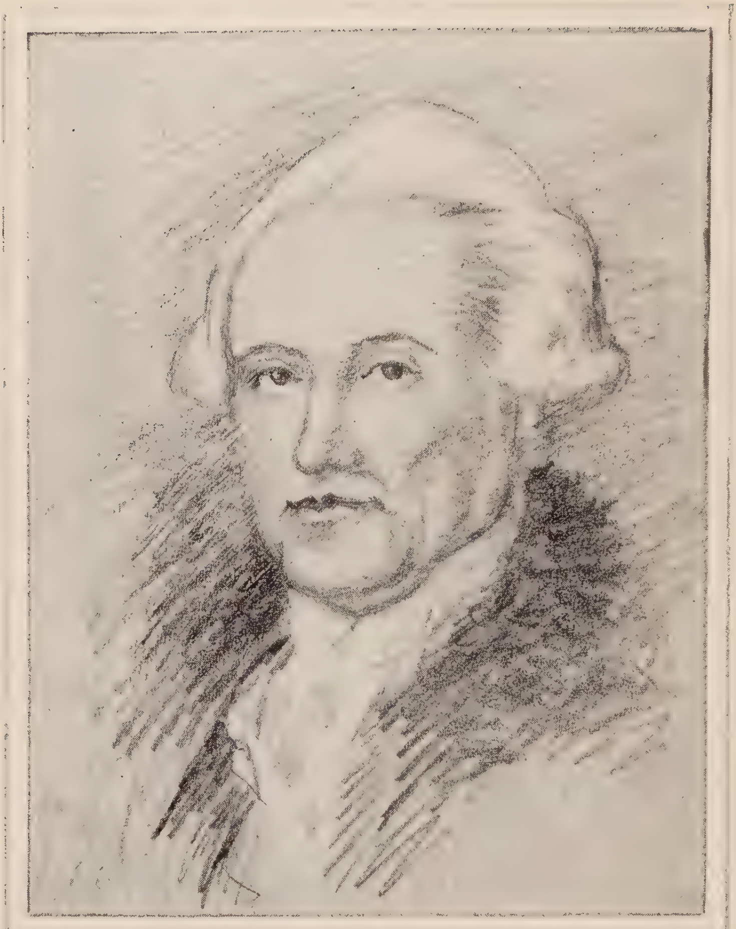

Plate XI: Frederick William Herschel (1738-1822)
(Pencil sketch, largely based on the pastel by I. Russell, R. A., dated 1794, as half-toned in Shapley and Howerth's *Source Book in Astronomy*)

with a mirror only a little over six inches in diameter, with a telescope-tube seven feet in length.

This was in 1781.

FIG. 46.—Caroline Herschel. (Adapted from Hutchinson's *Splendour of the Heavens*. Original source not traced.)

From that, Herschel went on to grind larger and better mirrors, until his fame as a telescope maker rivaled his fame as an observing astronomer.

His patience in grinding the curved reflecting surface was

monumental. Sometimes for sixteen hours together he must walk steadily about the mirror, polishing it without once removing his hands.

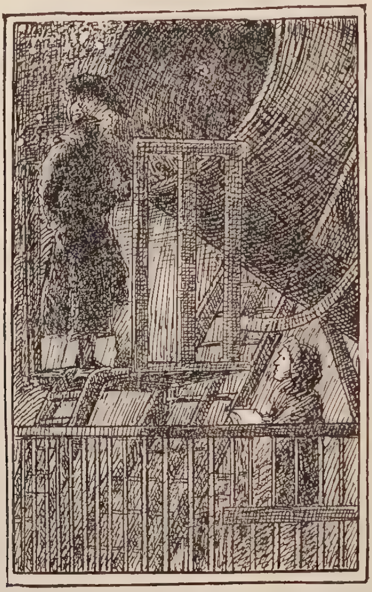

FIG. 47.—Herschel and His Sister at the Big Reflector. (Adapted from Williams' *Story of Nineteenth Century Science.* Original by T. de Thulstrup.)

Meantime his sister Caroline, always his chief lieutenant, cheers him with her presence, and from time to time puts food into his mouth.

A New World Discovered

The telescope completed, the astronomer turned night into day, and from sunset to sunrise, year in and year out, swept the heavens unceasingly, unless prevented by clouds or the brightness of the moon.

His sister sat always at his side, recording his observations. They were in the open air, perched high at the mouth of the

reflector, and sometimes it was so cold that the ink froze in the bottle in Caroline Herschel's hand; but the two enthusiasts hardly noticed a thing so commonplace as terrestrial weather. They were living in distant worlds.

The results? What could they be? Such enthusiasm would move mountains.

But, after all, the moving of mountains seems a Liliputian task compared with what Herschel really did with those wonderful telescopes. He moved worlds, stars, a universe—even, if you please, a galaxy of universes. At least he proved that they move, which seems scarcely less wonderful; and he expanded the cosmos, as man conceives it, to thousands of times the dimensions it had before.

As a mere beginning, he doubled the diameter of the solar system by observing the great outlying planet which we now call Uranus, but which he christened Georgium Sidus, in honor of his sovereign, and which his French contemporaries, not relishing that name, preferred to call Herschel.

When first seen, the planet was mistaken for a comet, its true character being revealed when its orbit was found to be broadly elliptical (almost circular), very different from the long, narrow ellipse of the comet's circuit.

This discovery was but a trifle compared with what Herschel did later, but it gave him world-wide reputation. Comets and moons aside, this was the first addition to the solar system that had been made within historic times, and it created a veritable furor of popular interest and enthusiasm. Incidentally King George was flattered at having a world named after him, and he smiled on the astronomer, and came with his court to have a look at his namesake.

The inspection was highly satisfactory; and presently the royal favor enabled the astronomer to escape the thraldom of teaching music and to devote his entire time to the more congenial task of star-gazing.

Presently, astronomy came to be almost a court function. King and Archbishop with their servitors came to visit the astronomer. The story goes that on one occasion, when the mammoth five-foot tube of the greatest of all telescopes was yet unmounted, the King led the way through the tube, calling out gayly, "My lord bishop, I will show you the way to heaven."

Whom the King smiles on prospers. So the astronomer soon had no need to worry about finances. Moreover, he presently married a wealthy widow, and thus was doubly entrenched against the wolf.

Exploring the Universe

Relieved from the burden of mundane embarrassment, Herschel turned with fresh enthusiasm to the skies, and his discoveries followed one another in bewildering profusion. He found various hitherto unseen moons of our sister planets; he made special studies of Saturn, and proved that this planet, with its rings, revolves on its axis; he scanned the spots on the sun, and suggested that they influence the weather of our earth; in short, he extended the entire field of solar astronomy.

But very soon this field became too small for him, and his most important researches carried him out into the regions of space compared with which the span of our solar system is a mere point.

With his perfected telescopes he entered abysmal vistas which no human eye had ever penetrated before, which no human mind had hitherto more than vaguely imagined.

He tells us that his forty-foot reflector will bring him light

from a distance of "at least eleven and three-fourths millions of millions of millions of miles"—light which left its source two million years ago.

The smallest stars visible to the unaided eye are those of the sixth magnitude; this telescope, he thinks, has power to reveal stars of the 1342nd magnitude. His system of magnitudes is not followed now, but the import of his estimates is unchallenged.

The Stars Are Suns

But what did Herschel learn regarding these awful depths of space and the stars that people them? That was what the world wished to know.

Copernicus, Galileo, Kepler, had given us a solar system, but the stars had been a mystery.

What says the great reflector—are the stars points of light, as the ancients taught, and as more than one philosopher of the eighteenth century has still contended, or are they suns, as others hold?

Herschel answers, they are suns, each and every one of all the millions—suns, many of them, larger than the one that is the centre of our tiny system.

Not only so, but they are moving suns. Instead of being fixed in space, as has been thought, they are whirling in gigantic orbits about some common centre.

Is our sun the centre?

Far from it. Our sun is only a star like all the rest, circling on with its attendant satellites—our giant sun a star, no different from myriad other stars, not even so large as some; a mere insignificant spark of matter in an infinite shower of sparks.

Here, then, the moving universe of Wright and Lambert and Kant finds a protagonist whose voice is loud.

Nor is this all. Looking beyond the few thousand stars that

are visible to the naked eye, Herschel sees series after series of more distant stars, marshalled in galaxies of millions; but at last he reaches a distance beyond which the galaxies no longer increase. And yet—so he thinks—he has not reached the limits of his vision.

What then? He has come to the bounds of the sidereal system—seen to the confines of the universe.

He believes that he can outline this system, this universe, and prove that it has the shape of an irregular globe, oblately flattened to almost dislike proportions, and divided at one edge—a bifurcation that is revealed even to the naked eye in the forking of the Milky Way.

The Scheme of the Universe

This, then, is our universe as Herschel conceives it—a vast galaxy of suns, held to one centre, revolving, poised in space.

But even here those marvellous telescopes do not pause. Far, far out beyond the confines of our universe, so far that the awful span of our own system might serve as a unit of measure, are revealed other systems, other universes, like our own, each composed, as he thinks, of myriads of suns, clustered like our galaxy into an isolated system—mere islands of matter in an infinite ocean of space.

So distant from our universe are these new universes of Herschel's discovery that their light reaches us only as a dim, nebulous glow, in most cases invisible to the unaided eye.

About a hundred of these nebulae were known when Herschel began his studies. Before the close of the century he had discovered about two thousand more of them, and many of these had been resolved by his largest telescopes into clusters of stars.

He believed that the farthest of these nebulae that he could see was at least three hundred thousand times as distant from

us as the nearest fixed star. Yet that nearest star—so more recent studies prove—is so remote that its light, travelling one hundred and eighty-six thousand miles a second, requires four and one-third years to reach our planet.

As if to give the finishing touches to this novel scheme of cosmology, Herschel, though in the main very little given to unsustained theorizing, allows himself the privilege of one belief that he cannot call upon his telescope to substantiate. He thinks that all the myriad suns of his numberless systems are instinct with life in the human sense.

Giordano Bruno and a long line of his followers had held that some of our sister planets may be inhabited, but Herschel extends the thought to include the moon, the sun, the stars—all the heavenly bodies.

He believes that he can demonstrate the habitability of our own sun, and reasoning from analogy, he is firmly convinced that all the suns of all the systems are "well supplied with inhabitants."

In this, as in some other inferences, Herschel is misled by the faulty physics of his time. Future generations, working with perfected instruments, may not sustain him all along the line of his observations, even, let alone his inferences.

But how one's egotism shrivels and shrinks as one grasps the import of his sweeping thoughts!

Origins

Continuing his observations of the innumerable nebulae, Herschel is led presently to another curious speculative inference. He notes that some star groups are much more thickly clustered than others, and he is led to infer that such varied clustering tells of varying ages of the different nebulae. He thinks that at first

all space may have been evenly sprinkled with the stars and that the grouping has resulted from the action of gravitation.

"That the Milky Way is a most extensive stratum of stars of various sizes admits no longer of lasting doubt," he declares, "and that our sun is actually one of the heavenly bodies belonging to it is as evident. I have now viewed and gauged this shining zone in almost every direction and find it composed of stars whose number . . . constantly increases and decreases in proportion to its apparent brightness to the naked eye."

"Let us suppose numberless stars of various sizes, scattered over an indefinite portion of space in such a manner as to be almost equally distributed throughout the whole. The laws of attraction which no doubt extend to the remotest regions of the fixed stars will operate in such a manner as most probably to produce the following effects:

"In the first case, since we have supposed the stars to be of various sizes, it will happen that a star, being considerably larger than its neighboring ones, will attract them more than they will be attracted by others that are immediately around them; by which means they will be, in time, as it were, condensed about a centre, or, in other words, form themselves into a cluster of stars of almost a globular figure, more or less regular, according to the size and distance of the surrounding stars. . . .

"The next case, which will also happen almost as frequently as the former, is where a few stars, though not superior in size to the rest, may chance to be rather nearer one another than the surrounding ones, and this construction admits of the utmost variety of shapes.

"From the composition and repeated conjunction of both the

foregoing formations, a third may be derived when many large stars, or combined small ones, are spread in long, extended, regular, or crooked rows, streaks, or branches; for they will also draw the surrounding stars, so as to produce figures of condensed stars curiously similar to the former which gave rise to these condensations.

"We may likewise admit still more extensive combinations; when, at the same time that a cluster of stars is forming at the one part of space, there may be another collection in a different but perhaps not far-distant quarter, which may occasion a mutual approach towards their own center of gravity.

"In the last place, as a natural conclusion of the former cases, there will be formed great cavities or vacancies by the retreating of the stars towards the various centres which attract them."

Looking forward, it appears that the time must come when all the suns of a system will be drawn together and destroyed by impact at a common centre. Already, it seems to Herschel, the thickest clusters have "outlived their usefulness" and are verging towards their doom.

But again, other nebulae present an appearance suggestive of an opposite condition. They are not resolvable into stars, but present an almost uniform appearance throughout, and are hence believed to be composed of a shining fluid, which in some instances is seen to be condensed at the centre into a glowing mass.

In such a nebula Herschel thinks he sees a sun in process of formation.

Taken together, these two conceptions outline a majestic cycle of world formation and world destruction—a broad scheme of cosmogony such as had been vaguely adumbrated two centuries before by Kepler and Descartes, and in more recent times by

Wright and Swedenborg and Kant. This so-called "nebular hypothesis" assumes that in the beginning all space was uniformly filled with cosmic matter in a state of nebular or "fire-mist" diffusion, "formless and void." It pictures the condensation—coagulation, if you will—of portions of this mass to form segregated masses, and the ultimate development out of these masses of the sidereal bodies that we see.

We shall learn in the succeeding chapter how this thesis was elaborated. The significance of the moment is that it now received the endorsement of the astronomer who had the ear of the public no less than of the world of science.

The Study of Double Stars

Yet another innovation. This time the record of certain double stars, which were reported in 1802 to the Royal Society as having changed their relative position toward one another since they were first charted twenty years before.

Hitherto it had been supposed that double stars were mere optical effect. Now it became clear that some of them, at any rate, are true "binary systems," linked together presumably by gravitation and revolving about one another.

Halley had shown, three-quarters of a century earlier, that the stars have an actual or "proper" motion in space; Herschel himself had proved that the sun shares this motion with the other stars. Here was another shift of place, hitherto quite unsuspected, to be reckoned with by the astronomer in fathoming sidereal secrets.

The double-star observations had been undertaken at first in the hope that these objects might aid the observer in ascertaining the actual distance of a star, through measurement of its annual parallax—that is to say, of the angle which the semi-radius of the earth's orbit would subtend as seen from the star. This

expectation was not fulfilled, but the demonstration that the law of gravitation holds sway in the depths of the sidereal universe was perhaps an even more important culmination of Herschel's labors than if the original object had been attained.

It gave the finishing touch to the conception of the starry heavens as a mechanism subject to natural laws—the same natural laws that control the planetary system, and the movements of ordinary bodies here on the earth's surface.

And now the culminating marvel.

The Sun Moves

Studying the "proper motions" of a few stars (seven in particular), Herschel drew the sagacious inference that the chief part of their motion is an optical effect—in reality a seeming backward drift, due to the actual forward flight of the solar system.

Noting the exact position of the "vanishing point" of the lines of apparent movement of the stars, he inferred that the sun's flight is in the opposite direction.

And so he located a region not far from the bright star Vega as the apex of the sun's flight.

The seven principal stars, Sirius, Castor, Procyon, Pollux, Regulus, Arcturus, and Alpha Aquilae were credited with the amounts and directions of movement given by Maskelyne in an account he had published of the proper motions of some principal stars. The list was supplemented by a table given by the French astronomer M. de Lalande, comprising twelve stars whose proper motions had been detected within the past fifty years.

Herschel states the opinion that, in view of the conformity of movement of these stars, we are no longer authorized to suppose the sun at rest, any more than we should be to deny the diurnal motion of the earth—except that the proofs of the latter

are very numerous, whereas the former rests only on a few testimonies.

He lists twenty-seven known motions of the stars on which his conclusions are based, which include but five deviations from consistency with his hypothesis.

These exceptions, he correctly adds, must be resolved into the real proper motion of the stars themselves, in contradistinction to the apparent motion due to the sun's shifting position.

Having pointed out the position of star Lambda Herculis as the apex of the sun's flight, Herschel adds a little later that this, after all, "is not perhaps the best selected. A somewhat more northern situation may agree better with the changes of declination of Arcturus and Sirius, which capital stars may perhaps be the most proper to lead us in this hypothesis."

Of all the many evidences of the genius of the greatest of observers, there is perhaps no more striking one than this. For the modern astronomer, with a multitude of stars from which to determine the vanishing point, fixes the direction of the sun's motion at a point only seven degrees northwest of Lambda Herculis.

Let me illustrate.

Look at the dial of your watch, when the minute-hand has passed the barest trifle more than a single minute beyond the hour-hand. Then the trifling angle between the two hands of the watch represents the difference between Herschel's estimate of the direction of the sun's flight and the most modern estimate. And the surmise with which the great astronomer qualifies his estimate, on the basis of the movements of two stars alone, brings the watch hands even closer together.

A large-scale architectural drawing in which all lines are di-

rected to a vanishing point with as small variation as that, would be considered an accurate piece of work.

But regardless of details as to exact direction, the marvel of marvels was to have shown that the sun is moving through space in a colossal flight. Herschel assumes as a justifiable inference that all the suns are moving. The dream of Kant has become an experimentally established astronomical hypothesis. The old cosmos of the "fixed" stars has been absolutely superseded.

Let it be noted that in this culminating achievement of his genius, Herschel is generalizing from observational data supplied by other astronomers. He, too, is a great observer. But unlike most great observers, he is not content merely with the records of facts, but must collocate the facts, and challenge their ultimate meanings. The sagacity of his inferences, coupled with their usual soundness, is the measure of his almost unparalleled genius.

"As a practical astronomer," says Holden, "Herschel remains without an equal. In profound philosophy he has few superiors. His is one of the few names which belong to the whole world."

XIX

KANT AND LAPLACE—THE NEW GENESIS

Immanuel Kant, world-famous as one of the greatest of philosophers, is known to everyone as the author of the *Critique of Pure Reason*. His genius is further attested by his less widely known speculations on the interpretation of the

sidereal universe of which we caught glimpses in an earlier chapter.

He conceived also the necessary slowing down of the earth's rotation through tidal friction arising from the moon's attraction.

Still more significantly, he speculated on the origin of the world and advanced a nebular hypothesis that anticipated the better known Laplacian theory by about forty years.

Let us learn from his own words how the imaginative philosopher conceived the world to have come into existence.

"I assume," says Kant, "that all the material of which the globes belonging to our solar system—all the planets and comets—consist, at the beginning of all things was decomposed into its primary elements, and filled the whole space of the universe in which the bodies formed out of it now revolve.

"This state of nature, when viewed in and by itself without any reference to a system, seems to be the very simplest that can follow upon nothing.

"At that time nothing has yet been formed. The construction of heavenly bodies at a distance from one another, their distances regulated by their attraction, their form arising out of the equilibrium of their collected matter, exhibit a later state.

"In a region of space filled in this manner, a universal repose could last only a moment. The elements have essential forces with which to put each other in motion, and thus are themselves a source of life. Matter immediately begins to strive to fashion itself. The scattered elements of a denser kind, by means of their attraction, gather from a sphere around them all the matter of less specific gravity; again, these elements themselves, together with the material which they have united with them, collect in those points where the particles of a still denser kind

are found; these in like manner join still denser particles, and so on.

"If we follow in imagination this process by which nature fashions itself into form through the whole extent of chaos, we easily perceive that all the results of the process would consist in the formation of divers masses which, when their formation was complete, would by the equality of their attraction be at rest and be forever unmoved.

"But nature has other forces in store which are specially exerted when matter is decomposed into fine particles. They are those forces by which these particles repel one another, and which, by their conflict with attractions, bring forth that movement which is, as it were, the lasting life of nature. This force of repulsion is manifested in the elasticity of vapors, the effluences of strong-smelling bodies, and the diffusion of all spirituous matters. This force is an uncontestable phenomenon of matter. It is by it that the elements, which may be falling to the point attracting them, are turned sideways promiscuously from their movement in a straight line; and their perpendicular fall thereby issues in circular movements, which encompass the centre towards which they were falling. In order to make the formation of the world more distinctly conceivable, we will limit our view by withdrawing it from the infinite universe of nature and directing it to a particular system, as the one which belongs to our sun.

"Having considered the generation of this system, we shall be able to advance to a similar consideration of the origin of the great world-systems, and thus to embrace the infinitude of the whole creation in one conception.

"From what has been said, it will appear that if a point is situated in a very large space where the attraction of the elements there situated acts more strongly than elsewhere, then the matter of the elementary particles scattered throughout the whole region will fall at that point. The first effect of this general fall is finally, that only those particles continue to move in this region of space which have acquired by their fall a velocity, and through the resistance of the other particles a direction, by which they can continue to maintain a free circular movement. . . .

"The view of the formation of the planets in this system has the advantage over every other possible theory in holding that the origin of the movements, and the position of the orbits in arising at that same point of time—nay, more, in showing that even the deviations from the greatest possible exactness in their determinations, as well as the accordances themselves, become clear at a glance. The planets are formed out of particles which, at the distance at which they move, have exact movements in circular orbits; and therefore the masses composed out of them will continue the same movements and at the same rate and in the same direction."

There is much more in kind, but after all is said it must be admitted that the explanation leaves a good deal to be desired.

It is the explanation of a metaphysician rather than that of a mathematician.

Such phrases as "matter immediately begins to strive to fashion itself," for example, have no place in the reasoning of inductive science. Nevertheless, the hypothesis of Kant is a remarkable conception; it attempts to explain along rational lines something which hitherto had for the most part been considered altogether inexplicable.

Plate XII: Pierre Simon Laplace (1749-1827)
(Pencil sketch based on the painting by Nedeon, as transcribed by an unknown engraver, and half-toned in Williams' *History of Science*)

But there are various questions that at once suggest themselves which the Kantian theory leaves unanswered.

How happens it, for example, that the cosmic mass which gave birth to our solar system was divided into several planetary bodies instead of remaining a single mass? Were the planets struck from the sun by the chance impact of comets, as Buffon has suggested? or thrown out by explosive volcanic action, in accordance with the theory of Dr. Erasmus Darwin? or do they owe their origin to some unknown law?

In any event, how chanced it that all were projected in nearly the same plane as we now find them?

Laplace and the Nebular Hypothesis

It remained for a mathematical astronomer to solve these puzzles.

The man of all others competent to take the subject in hand was the French astronomer Laplace. For a quarter of a century he had devoted his transcendent mathematical abilities to the solution of problems of motion of the heavenly bodies. Working in friendly rivalry with his countryman Lagrange, his only peer among the mathematicians of the age, he had taken up and solved one by one the problems that Newton left obscure.

Largely through the efforts of these two men the last lingering doubts as to the solidarity of the Newtonian hypothesis of universal gravitation had been removed.

The share of Lagrange was hardly less than that of his co-worker; but Laplace will longer be remembered, because he ultimately brought his completed labors into a system, and, incorporating with them the labors of his contemporaries, produced in the *Mécanique Céleste* the undisputed mathematical monument of the century, a fitting complement to the *Principia* of Newton, which it supplements and in a sense completes.

In the closing years of the eighteenth century Laplace took up the nebular hypothesis of cosmogony, to which we have just referred, and gave it definite proportions; in fact, made it so thoroughly his own that posterity will always link it with his name.

Discarding the crude notions of cometary impact and vol-

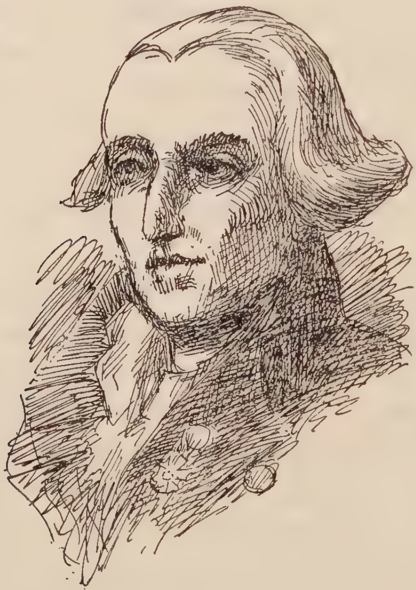

Fig. 48.—Joseph Louis Lagrange. (Redrawn from Williams' *Story of Nineteenth Century Science.* Original not traced.)

canic eruption, Laplace filled up the gaps in the hypothesis with the aid of well-known laws of gravitation and motion.

He assumed that the primitive mass of cosmic matter which was destined to form our solar system was revolving on its axis even at a time when it was still nebular in character, and filled all space to a distance far beyond the present limits of the system.

As this vaporous mass contracted through loss of heat, it

revolved more and more swiftly, and from time to time, through balance of forces at its periphery, rings of its substance were whirled off and left revolving there, subsequently to become condensed into planets, and in their turn whirl off minor rings that became moons.

The main body of the original mass remains in the present as the still contracting and rotating body which we call the sun.

The nebular hypothesis thus given detailed mathematical completion by Laplace is justly regarded as a worthy compliment of the grand cosmologic scheme of Herschel. Whether true or false, the two conceptions stand as the final contributions of the eighteenth century to the history of man's ceaseless efforts to solve the mysteries of cosmic origin and cosmic structure.

The world listened eagerly and without prejudice to the new doctrines; and that attitude tells of a marvellous intellectual growth of our race.

Mark the transition:

In the year 1600, Bruno was burned at the stake for teaching that our earth is not the centre of the universe, and the plurality of worlds. In 1700, Newton was pronounced "impious and heretical" by a large school of philosophers for declaring that the force which holds the planets in their orbits is universal gravitation. In 1800, Laplace and Herschel are honored for teaching that gravitation built up the system which it still controls; that our universe is but a minor nebula, our sun but a minor star, our earth a mere atom of matter, our race only one of myriad races peopling an infinity of worlds.

Doctrines which but the span of two human lives before would have brought their enunciators to the stake, are now pronounced not impious, but sublime.

Making the Generation Star-Minded

Both Laplace and Herschel lived on well into the new century. Herschel, eleven years the elder, died in 1822, aged 84. Laplace died in 1827, at the age of 78. But the great work of both had been carried far toward completion in the 18th century, and counted among the crowning achievements of that century.

The value of their work was not merely astronomical, in the restricted sense of the word.

Herschel's great accomplishment was to make his generation star-minded, if the phrase be permitted—to bring to the attention of the world at large a comprehension of the stupendous size and complexity of the sidereal system, in contrast to the relative smallness and simplicity of the solar system, even though that system itself had been doubled in size.

The work of Laplace had been to present the universe as a mechanism subject to natural law, and to suggest a rational explanation of the evolution of the solar system—an astronomer's conception of the creation of the world.

The world in which Herschel and Laplace died was a very different world from that into which they had been born. And for the change they, more than any other men, were responsible.

In the broader view it seems a matter of indifference that a soldier named Napoleon chanced to live in the same epoch. The fact that James Watt, developer of the steam engine, was also a contemporary, is of greater moment. But after all, what is material progress that was to eventuate in a machine age, in comparison with intellectual awakening that was to lead to the emancipation of the human spirit from an age-long thraldom?

E pur si muove

And now an amazing thing happened. In the very year of Herschel's passing, and while Laplace had yet five years to live,

the works of Copernicus, Kepler, and Galileo were officially expunged from the *Index*.

Thus was the year 1822 made memorable.

Herschel's telescopes and the pencil of Laplace had been determining factors in accomplishing this liberative denouement.

Herschel had added to the planetary system a body sixty times the bulk of the earth and from a billion and a half to two billion miles away, (in the various sectors of its orbit). Could any rational being be asked to believe that the little earth stands still while this great globe makes a five-billion-mile circuit about it in twenty-four hours?

Laplace had explained the origin of the solar system, and brought the world mechanism under the dominion of natural law.

And the work of both had been accomplished as culminating additions to the conception of the new cosmology which began with Copernicus and was extended by an unbroken sequence of worthy successors.

Item by item the new elements had been added to complete the structure. Galileo's telescope revealed the planetary system of Jupiter. Kepler established the laws of planetary revolution. Horrox and Flamsteed magnified the sun and solar system. Newton brought the universe within the compass of his law of gravitation. Halley brought the comet into the sun's planetary family, and showed the stars moving in the firmament.

The scheduled return of Halley's comet in 1758, coupled with the inescapable verdict of the multitudes of Bradley's nodding stars prepared the world for the expansion of the solar system and the sounding of the universe by Herschel's telescopes, and for the new mathematical Genesis of Laplace.

The Index Was Wrong

The cumulative evidence could no longer be withstood. It was time quietly to blue-pencil the *Index*.

The new edition, to be published in 1835, would not bear the names of the traditional heretics who had challenged the orthodox conception of the geocentric universe.

The blue-penciling had been rather long delayed. Copernicus had been dead almost three centuries, Kepler little less than two centuries, Galileo 180 years. But Rome was not built in a day, and the breaking down of a tradition is a far more formidable task than the building of a city.

Let it suffice that thenceforward the most devout churchman could read about, talk about, the sun and the earth in rational terms without stultifying himself or being false to his religion.

Thenceforward our planet could rotate on its axis—"Sleep on its soft axle" in Milton's inspired phrase—and swing round its orbit with the sanction of infallible authority, which until now had condemned it to perpetual immobility.

So Galileo was right, after all. *E pur si muove*. The planet Earth *does* move.

And the world of thought moves too!

BOOK V

THE ASTRONOMY OF PRECISION

"Contemplated as a whole, astronomy is the most beautiful monument of the human mind, the noblest record of its intelligence."

—*Laplace.*

XX

PIAZZI—OLBERS—A GALAXY OF NEW WORLDS

THE first day of the nineteenth century was fittingly signalized by the discovery of a new world. On the evening of January 1, 1801, an Italian astronomer, Piazzi, observed an apparent star of about the eighth magnitude (hence, of course, quite invisible to the unaided eye), which later on was seen to have moved, and was thus shown to be vastly nearer the earth than any true star.

He at first supposed, as Herschel had done when he first saw Uranus, that the unfamiliar body was a comet; but later observation proved it a tiny planet, occupying a position in space between Mars and Jupiter.

It was christened Ceres, after the tutelary goddess of Sicily.

Though unpremeditated, this discovery was not unexpected, for astronomers had long surmised the existence of a planet in the wide gap between Mars and Jupiter. Indeed they were even preparing to make concerted search for it, despite the protests of philosophers, who argued that the planets could not possibly exceed the magic number seven, when Piazzi forestalled their efforts.

Thus it was the peculiar distinction of the new-found planet to give the quietus to an age-old superstition. The story is this:

The ancient Babylonians, it will be recalled, counted seven planetary bodies—the Moon, the Sun, Mercury, Venus, Mars, Jupiter, and Saturn. As each was the abode of an important god

(or perhaps a hierarchy of gods) the number seven was not unnaturally inferred to have peculiar significance.

It became the sacred number in the estimate of the philosopher-priests whose business it was to attend to such matters.

Hence the old Babylonian Creation-Tablets told of seven days of world-making, and Semitic records bristled (as every one who knows his Genesis-to-Revelations can attest) with sacred *sevens* —from spirits of God, years of plenty, golden candlesticks, and sacrificial lambs, rams, and bullocks, to the same cabalistic number of last plagues and abominations.

And as the Oriental ideas permeated westward, and the number of heavenly bodies was long unexpanded, we hear of the universal acceptance of the seven-day week and the seven-day Creation-Period; not to mention such incidental symbolisms as the seven wise men of Greece and the Seven Wonders of the classical world.

One might have supposed that the cabalistic number would have lost something of its traditional significance after the Copernican upheaval, which changed the count of planetary bodies. The sun being removed from the hierarchy (or enthroned in the Holy of Holies) and the moon reduced to a subordinate position, there were now but six planets, even though the earth supplied the place vacated by the sun in the census.

But philosophers are fertile in expedients, and it was necessary only to include the stellar sphere to bring the count back to the ideal number.

And then, in due course, came Herschel, with the discovery of Uranus, and it was only necessary again to ignore the sphere of the stars to vindicate the inspired wisdom of the ancient

Orientals—the count of actual planets being once more unchallengeably Seven.

Obviously, man's astronomical wisdom was at last complete. The Perfect solar system, of approved cabalistic design, stood revealed. There remained nothing to discover.

So reasoned Hegel, Germany's great philosopher, at the close of the eighteenth century.

He reasoned with pious fervor, and not without cause, for it appeared that iconoclastic astronomers of the period had raised a question as to whether there should not be another planet, to occupy what seemed to them a gap in the sequence of the planetary bodies, between Mars and Jupiter.

Bode's Law

An astronomer named Bode had devised a sort of rule-of-thumb which he brought to the attention of the world in 1772 (one Titius of Wittenberg is said to have conceived a similar idea even earlier), according to which there is a curious kind of regularity in the relations of interplanetary spaces one to another.

The scheme is this:

Write a series of 4's. To the second 4 add 3; to the third add 3x2, or 6; to the fourth, 3x4, or 12; and so on, doubling the added number each time, as in the accompanying scheme.

4	4	4	4	4	4	4
	3	6	12	48	96	192
	—	—	—	—	—	—
	7	10	16	52	100	196
Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus

The resulting numbers, divided by 10, are pretty nearly the true mean distances of the planets from the sun, in terms of the radius of the earth's orbit.

Professor Young, whose table I am here using, goes on to say that the "law" breaks down completely in the case of Neptune. But of course Neptune was not yet discovered when the law was put forward. And the significant thing at the moment is that there was no planetary body at all to occupy the position between Mars and Jupiter, where the "law" urgently called for such a body.

Hence the proposed quest of the astronomers.

And now speaks the voice of authority. The Olympic Hegel rebuked the iconoclasts; pointed out that since seven planets were already known, it would be not only futile but hardly less than impious to attempt to find another. Never yet was there true epistomologist for whom metaphysical traditions did not have the force of unalterable law.

Piazzi's Discovery

But just at the moment when the mandate of the oracle was uttered, a practical star-gazer down in Italy, the hitherto obscure Piazzi, fixed his telescope by accident on an unknown star that wandered a little, and so at first was thought to be a comet, but which was presently shown to be a planetary body occupying precisely the position between Mars and Jupiter where Bode's rule-of-thumb table showed a vacancy.

A very small planet, it is true; but a body circling about the sun precisely as the other planets do—a major planet in position, even if only a very minor one in size.

Almost a profane body, in the eye of tradition, because it added an eighth to the already complete coterie of the solar hierarchy.

A small planet, yet large enough to challenge effectively the sacredness of that cabalistic number seven, which had so strangely dominated the minds of the oriental dreamers, and which (de-

spite the planetary exorcism) would still continue to cast its shadow across the path of civilization for generations to come.

Superstition, like the scotched snake, does not instantly release its coils, when new truth gives it quietus; but the discovery of the eighth planet gave sure augury of a time when the mystic seven would cease to be potent in human affairs—when, for example, it would not longer be considered impious to conduct normal human activities on the seventh day of the week. Perhaps, even, when the seven-day week itself would be superseded by a more convenient unit.

Once more astronomy had achieved a triumph—or near triumph—over anthropomorphic tradition.

A Great Physician-Astronomer

But now came a surprise for the astronomers in their turn. For the very next year, Dr. William Olbers, the wonderful physician-astronomer of Bremen, while following up the course of Ceres, happened on another tiny moving star, similarly located, which soon revealed itself as planetary. Thus two planets were found where only one had been expected.

Dr. Olbers, who made the discovery, was one of the company of famous astronomers (as Piazzi was not) who had been on the point of searching for the new world when the Italian anticipated their quest. To his discovery, owing to his fame, there attached a measure of authenticity that did not attach to the observation of the less-known Italian. The fact that a second planet existed, in about the same orbit as the first, was puzzling. We shall see in a moment that Dr. Olbers himself offered the explanation.

But before that we must pause to learn something about the physician-astronomer himself.

The name of Heinrich Wilhelm Mathias Olbers—how Teu-

tonically sonorous a collocation!—is one of the great names in the annals of astronomy.

It almost rivaled the names of Herschel and Laplace, whose owners were slightly elder contemporaries of the physician-astronomer, during the first quarter of the 19th century; matched the names of the slightly younger contemporaries Bessel and Struve in the ensuing decade; and became a permanent remembrance, as that of one who had made fundamental contributions both to fact and to theory in the field of solar astronomy.

Dr. Olbers was another of the notable company of astronomers who achieved fame as an amateur.

Like Bradley and Herschel he had another profession than star-gazing when he made his momentous discoveries. But unlike the others he remained an amateur to the end of his life. For forty years he practiced medicine at Bremen, and when he retired from his vocation, he continued to practice his avocation during the goodly term of "improbable years" allotted him, in his own private observatory, at the top of the house where he had all along resided.

Again, this amateur astronomer had precocity of genius—like Horrox and Halley of the earlier centuries and Goodricke, his own early contemporary. And like Halley (but not the other two) he was to live, as we have seen, to follow up the promise of his youth, and to show that brilliant early achievement does not necessarily exhaust the flame of genius.

A Twenty-Hour Work Day

You may ask how a man who was occupied year after year in the arduous practice of the medical profession found time to compete on a par in accomplishment of practical observation and of mathematical speculation with the great professional exemplars of another profession.

The answer is that the exceptional physical endowment of the Bremen physician made this readily possible. Throughout his life he enjoyed superb health. And he was so constituted that he required only four hours of sleep out of twenty-four.

Thus each day he had twenty hours of conscious life, as against the sixteen hours of the average mortal.

If you will make a brief computation, simple arithmetic will show you that this means 140 hours in which to be really *alive,* instead of 112, each week—7280 living hours per year, instead of 5820. Virtually a gain of 1460 hours of life per year. And the Bremen physician had full three score such years in which to utilize those extra hours, beyond the time when, while yet a medical student, he performed the feat which gave him fame in the astronomical world.

The accredited span of his life was 82 years; but the hours of his conscious activity were those of a centenarian.

A Mathematical Physician

The accomplishment that gained fame for young Olbers while he was a medical student, was of a character to show not alone precocity but versatility of genius. For it was a mathematical calculation—the demonstration of an original method of computing the orbit of a comet.

That is not the kind of investigation that one would expect of a medical student, genius or no genius.

But this particular medical student had a penchant for the physical sciences no less than for the biological. At Göttingen, while his chief business was the study of medicine, he attended lectures in mathematics also.

Doubtless the 20-hour day gave him time for this, while he could still keep in the van of his medical classmates.

It was while watching at the bedside of one of these confrères,

on a memorable night, that young Olbers thought to pass the time of vigil, while the sick companion slept, by speculating on the mysteries of the orbit of comets, a subject then—as before and long after—of particular interest to astronomers, and of more than incidental interest to the public at large, as bearing on the question of the supernatural origin of these strange visitants.

Needless to say, the young medico had no illusion as to the "natural" state of comets. He was concerned only to find a way of computing the orbit of a comet, based on three or four observations, so that the whereabouts of the comet during the long term when it was not near enough to be visible could be predicated.

Sitting there in the sick room that night, he found such a method—thanks to his native endowment of imaginative genius, fortified by acquired knowledge of mathematics.

Considering only comets in general and not any particular individual of the clan, he developed a formula, based on three suppositions whereby, using four equations, "treating as unknown the curtate distances of the comet from the earth, the assumption that seems to me the most tractable," the problem was solved.

The precise equations involved, and their solution, are matters only for the initiate. But competent critics of our own time declare that this was the first satisfactory method for determining cometary orbits, and that it remains the accepted method of our own day.

That was a strange outcome of a young man's vigil at the bedside of a medical classmate.

Had not the classmate fallen ill, it is not unlikely that the comet might for another generation or two have maintained its

Plate XIII: Heinrich Wilhelm Matthias Olbers (1758-1851)
(Crow-quill interpretation of engraving in Williams' *Story of Nineteenth Century Science*. Original source untraced)

traditional role of an erratic messenger, whose vagaries spelled puzzlement even for the astronomer.

Halley, himself a mathematical genius, had indeed unmasked the comet a century before, predicting the return of the member of the family that (coming back obediently in 1758) was thence forth to bear his name.

But it remained for young Olbers to complete the disrobement of the spectacular pretender, and to place in the hands of the astronomers a mathematical apparatus by which they could expeditiously demonstrate that any new comet that might appear could be brought into the orderly scheme of movement of other bodies of the planetary system.

New Comets and Planets

We shall see a little later that the young man who thus bearded the comet in its orbit was at a later day—now become a full fledged medico, pursuing his vocation at Bremen—to complete the humiliation of the comet by his natural explanation of the spectacular appendage which had all along been the chief stock in trade of the comet as a terrorizer.

Also that the physician, peering through his telescope during those extra hours of the night when most folks are asleep, was to discover sundry new comets, notably a spectacular one in 1815, which thence forth was to bear his name.

But for the moment we are concerned chiefly with more conventional members of the planetary family; in particular with the newly discovered company occupying that vacant space between Mars and Jupiter, whose second member, as we have seen, fell to the telescope of the physician-astronomer of Bremen.

There is, to be sure, an apparent relationship between these little planets—which were variously christened "asteroids" and "planetoids"—since small tailless comets, which are far more

abundant than large ones with tails, may readily be mistaken for little planets of the new order.

We have seen that Piazzi, when he first saw Ceres, mistook it for a comet. Its planetary nature was demonstrated only when its orbit had been charted by the mathematician Gauss. And, indeed, the new planets, because of their exceedingly small size, seemed almost as anomalous members of the sun's family as the comets themselves.

There was this notable difference, however, that the little planetoids were swinging about the sun in elliptical orbits quite comparable to those of the major planets.

Characteristics of the New Planets

The small size of the newcomers made it seem rather less strange that they were twins, so to speak, yet was a fact calling for explanation.

The explanation came from Dr. Olbers himself, who suggested that Ceres and Pallas, as he called his captive, might be fragments of a quondam full-sized planet that had been shattered by internal explosion or by the impact of a comet. Other similar fragments, he ventured to predict, would be found when searched for.

William Herschel gave the sanction of his great authority to this theory, and suggested the name asteroids for the tiny planets.

The explosion theory was supported by the discovery of another asteroid (or planetoid as they are now preferentially called) by Harding, of Lilienthal, in 1804, and it seemed clinched when Olbers himself found a fourth in 1807.

The new-comers were named June and Vesta respectively.

At a later day, as we shall see, the finding of new planetoids was to become a commonplace, though the fifth member of the clan was not discovered until 1845, when a Prussian amateur

astronomer named Hencke, by this discovery, aroused new interest and started a lasting fashion in planetoid-hunting.

We shall hear more about the planetoids later. Here it remains only to say an additional word about the explosion theory, of their origin. Dr. Olbers advanced the theory tentatively, but it came to be generally accepted. It seemed to explain the anomaly that the largest of the new members of the sisterhood of planets were but a few hundreds of miles in diameter.

But, as is the fate of theories in general, when given recognition chiefly because of the fame of their proponent, this explosion theory was destined to be discredited after a generation or two of popularity.

When, at a later day, many planetoids were in evidence, it was found that their orbits of revolution do not have any one point of intersection, as might be expected if they are all of a common origin, and this fact was held to negative the explosion theory. It chanced that the first four planetoids discovered do have intersecting orbits. It was admitted, too, that gravitational disturbances might have perturbed the orbits of the little planets so that they would no longer coincide even if they had originally done so.

But on the whole, the evidence seemed to cold-shoulder the explosion hypothesis.

And yet, in our own day—and here again history repeats itself—the Olbers theory has been revived, in slightly modified form. It is suggested that the planetoids might plausibly be accounted for as fragments of a planet of similar orbit, which inadvertently came too near the giant Jupiter and so through operation of the principle of what is called Roche's limit (with

which we shall elsewhere make further acquaintance) was disrupted and strung out into fragments with explosive abruptness.

So perhaps the physician-astronomer was right after all. In any event, the new system of planetoids, like the new theory of comets, must always be associated with his name.

XXI

JOHN HERSCHEL—STRUVE—BESSEL—SOUNDING THE UNIVERSE

When John Herschel, the only son and worthy successor of the great Sir William, began star-gazing in earnest, after graduating senior wrangler at Cambridge, and making two or three tentative professional starts in other directions to which his versatile genius impelled him, his first extended work was the observation of his father's double stars. His studies, in which at first he had the collaboration of James South, brought to light scores of hitherto unrecognized pairs, and gave fresh data for the calculation of the orbits of those longer known.

So also did the independent researches of F. G. Struve, the enthusiastic director of the famous Russian observatory at the University of Dorpat, and subsequently at Pulkowa.

Utilizing data gathered by these observers, M. Savary, of Paris, showed, in 1827, that the observed elliptical orbits of the double stars are explicable by the ordinary laws of gravitation, thus confirming the assumption that Newton's laws apply to

these sidereal bodies. Henceforth there could be no reason to doubt that the same force which holds terrestrial objects on our globe pulls at each and every particle of matter throughout the visible universe.

The pioneer explorers of the double stars early found that the systems into which the stars are linked are by no means con-

FIG. 49.—Friedrich Georg Wilhelm von Struve (1793-1864). (Redrawn from Shapley and Howarth's *Source Book in Astronomy.* Source of original not stated.)

fined to single pairs. Often three or four stars are found thus closely connected into gravitation systems; indeed, there are all gradations between binary systems and great clusters containing hundreds or even thousands of members.

It is known, for example, that the familiar cluster of the Pleiades is not merely an optical grouping, as was formerly supposed, but an actual federation of associated stars, some two

thousand five hundred in number, only a few of which are visible to the unaided eye. And the more carefully the motions of the stars were studied, the more evident it became that widely separated stars are linked together into infinitely complex systems, as yet but little understood. At the same time, all instrumental advances tended to resolve more and more seemingly single stars into close pairs and minor clusters.

The two Herschels between them discovered some thousands of these close multiple systems; Struve and others increased the list to above ten thousand; and at a later day, S. W. Burnham, the most enthusiastic and successful of double-star pursuers, added a thousand new discoveries while he was still an amateur in astronomy and by profession the stenographer of a Chicago court.

It began to be clear that the actual number of multiple stars is beyond all present estimate.

The elder Herschel's early studies of double stars were undertaken in the hope that these objects might aid him in ascertaining the actual distance of a star, through measurement of its annual parallax—that is to say, of the angle which the semi-diameter of the earth's orbit would subtend as seen from the star.

The expectation was not fulfilled. The apparent shift of the position of a star as viewed from opposite sides of the earth's orbit, from which the parallax might be estimated, is so extremely minute that it proved utterly inappreciable, even to the almost preternaturally acute vision of Herschel, with the aid of any instrumental means then at command. So the problem of star distance allured and eluded him to the end, and he died in 1822 without seeing it even in prospect of solution.

His estimate of the minimum distance of the nearest star,

based though it was on the somewhat fallacious test of apparent brilliancy, was a singularly sagacious one, but it was at best a scientific guess, not a scientific measurement.

Sir John Herschel at the Cape of Good Hope

John Herschel had not the dynamic genius of his father—there are not two men like the elder Herschel born in any century—but he was none the less a man of brilliant intellect. In charm of personality he ranks with his forerunner Halley, as also in breadth of culture and variety of interests.

While still a young man, Herschel confirmed his father's discoveries of nebulae, adding many new nebulae and clusters. He also added more than 3000 new double stars to the list his father compiled.

Doubtless he had learned the art of telescope-making from his father. At all events, he made an eighteen-inch reflector of the finest quality—and the making of large reflectors was an art that the elder Herschel had developed for himself, and in which he had no competitor.

In 1834, John Herschel went to the Cape of Good Hope, where he remained for four years, and did a very remarkable piece of work in the way of gauging fields of stars. His method, originally devised by his father, was to count the stars in here and there a field—it being quite impossible in any one man's life time to count more than a small fraction of the total number in the sky, as revealed by a large telescope. The number of fields in which he did make the count, however, was 2299. He also measured over 2000 double stars and nearly 2000 nebulae. In particular he examined with great care the remarkable "Magellanic Clouds," a pair of nebulae that are among the outstanding spectacles of the southern hemisphere.

In those pre-photographic days, every star had to be located

by individual observation. Moreover the telescopes had no mechanical driving apparatus to keep them fixed on the star. And needless to say there was no electrical equipment for convenient shifting of domes or platforms.

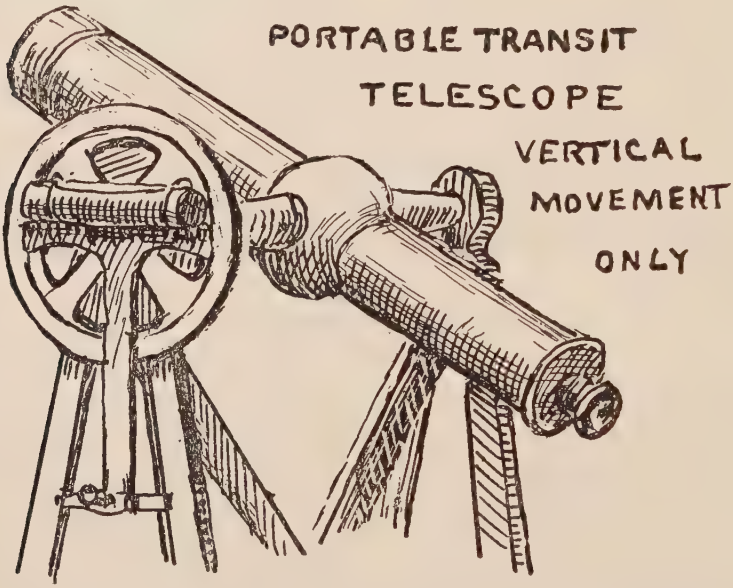

FIG. 50.—This type of meridional mounting is indispensable for noting the exact time of a star's meridian passage, but cannot follow the star.

Modern observers, accustomed to these mechanical aids, look back with astonishment upon the work achieved by Herschel and his fellow workers of that period, when star-charting meant star-gazing hour after hour, accompanied by a by no means negligible modicum of manual labor.

The reflecting telescope is adapted rather for surveying considerable fields of stars, interpreting nebulae, and general celestial map-making, rather than for meticulous measurement of the

position and possible movement of individual stars. In any event, it was this field of star gauging, to gain an idea of the actual number of stars in the celestial system (by comparing the aggregate area of the fields gauged with the total area of the heavens) that engaged Herschel's attention. He dealt with stars

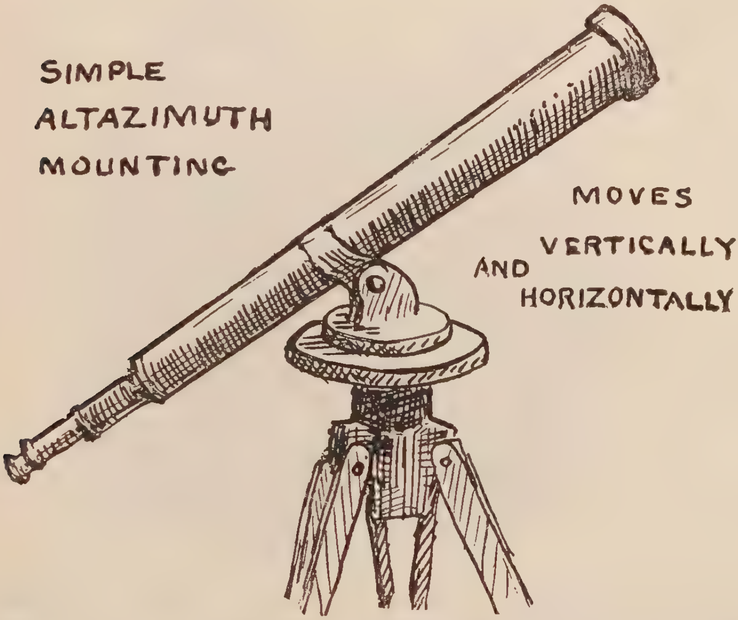

FIG. 51.—Mounted thus the telescope does not follow a star when rotated unless constantly shifted meridianly.

en masse, rather than with individual members of the sidereal family.

There were other equally assiduous star-gazers, however, who worked with instruments of a different type, and while devoting no little time to star-charting, gave attention also to specialized studies of individual stars, in the hope of solving the old elusive problem of parallax.

Foremost among these were the Russian astronomer, Friedrich Georg Wilhelm Struve (1793-1864), first director of the Pulkova Observatory, and the German Friedrich Wilhelm Bessel (1784-1846), director of the observatory at Königsberg. Both these men, working independently at the same problem, achieved

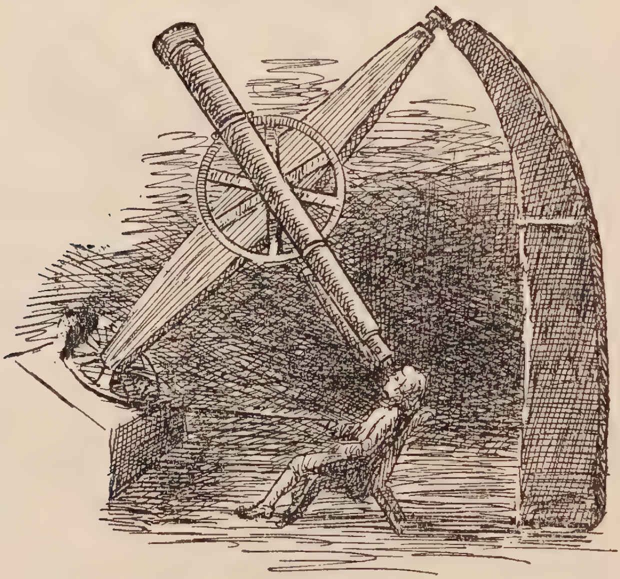

FIG. 52.—A Primitive But Typical "English" Equatorial Mounting. (Adapted from Chambers' *Pictorial Astronomy*.) The upright support is parallel to the earth's polar axis; therefore the rotating telescope follows the path of a sidereal body.

the hitherto impossible. It was Bessel, however, whose work first received official recognition, as we shall see in a moment.

From Counting-House to Observatory

Bessel, come now to be the foremost astronomer of Europe, was originally a protégé of the great Dr. Olbers.

Indeed, Olbers was accustomed to declare that the greatest service he ever rendered astronomy was the discovery of Bessel.

When the youth first came to the attention of the great physi-

cian-astronomer, he was acting as a clerk in a Bremen mercantile house. Olbers presently secured for him the post of assistant in the observatory at Lilienthal, with a salary of one hundred thalers a year.

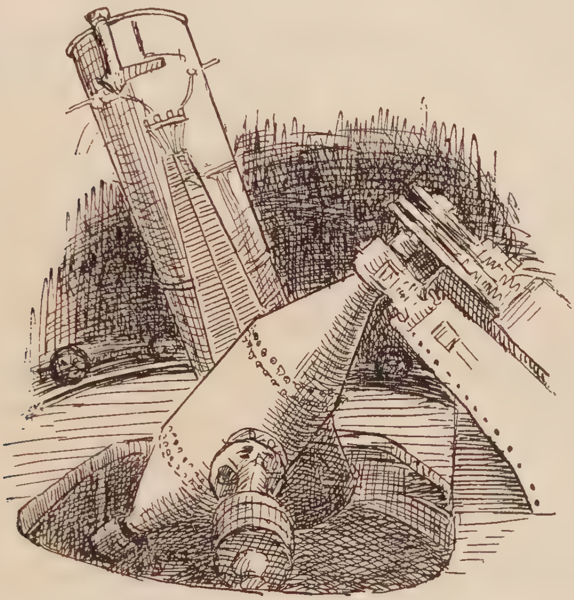

FIG. 53.—Reflecting Telescope on "English" Equatorial Mounting. (Adapted from photograph of the Crossley Reflector at Lick Observatory.)

After that Bessel was able to account for himself, but he remained very grateful to his benefactor, and Olbers, to the day of his death, regarded his successor with the affection of a father.

It was no mere personal liking, however, but the recognition of sterling qualities that led Dr. Olbers in the first instance to take an interest in the young clerk.

Young Bessel was preeminently distinguished from boyhood

with those qualities of "ambition, imagination, and the will to work" which have been predicated by a philosopher of our own day as the guarantees of success.

Thus we are told that the clerk, "wishing to travel, and seeing a possible opening as supercargo, studied languages, geography, picked up all sorts of information on the habits of distant peoples, and learned something of navigation. And from navigation, he was led on to astronomy and mathematics."

I am here quoting our own distinguished astronomer, Dr. Charles G. Abbot, of the Smithsonian Institution, who goes on to say that Bessel "made for himself a sextant, and, observing, with the aid of a common clock, amused himself with determining the longitude of Bremen. This fixed his career. Coming upon some old observations of Halley's comet, Bessel deduced from them so good an orbit as to charm the celebrated Olbers, who caused the work to be published."

That was how it came about that Dr. Olbers presently secured the position for Bessel in the observatory. Meantime the young enthusiast had filled in his leisure hours by mastering the calculus and the *Mécanique Céleste,* of Laplace—that great work which ranks only second to Newton's *Principia* among the mathematical productions of the modern epoch.

One might continue the story by telling how Bessel at a later day, after he had gained fame by developing a mathematical method for "reducing" the positions of the stars (for telluric and solar parallax, for refraction of light, for precession, aberration, and nutation), thus giving new value to the old star-craft, and had made a wonderful star-chart of his own with a census of 50,000 stars, discovered a young man named Argelander, and

drew him away from the counting house, even as Olbers had drawn himself away.

And how this Argelander was famous in a later day for publishing the great "Bonn Durchmusterung"—a star-chart with corresponding "Atlas" in which are found places and brightness of over 324,000 stars, including all in the northern heavens to the 9th magnitude, or some twenty times fainter than the eye can see.

The story might be completed by noting that one of Argelander's pupils, the American B. A. Gould, extended the "Durchmusterung" to the south pole of the heavens, producing a chart of the southern hemisphere that ranks among the great historical star-maps.

Bessel Announces His Victory

But although these are matters of no small interest, our present concern is mainly with that most spectacular of all Bessel's achievements, the determination of the parallax of a star.

It was under date of October 23, 1838, that the now famous German astronomer wrote a personal letter to the equally famous Sir John Herschel, who had recently returned to England from his famous exploration of the southern heavens.

The letter itself became at once an historical document of no little significance in the archives of astronomy. For it told of the solving of a star-problem that had foiled hundreds of searchers of earlier generations.

In a word, Bessel had succeeded at last in measuring the parallax of a star.

His letter refers to this as the "obtaining of a long-looked-for result," which he presumes will interest so great and zealous an explorer of the heavens as Herschel, whom he addresses directly

because, speaking to a colleague, he can write in his own language, and thus secure his meaning from indistinctness.

Needless to say the letter was received with enthusiasm. The technical data it contained were placed before the council of the Royal Astronomical Society, and in due course it was adjudged that Bessel had indeed attained the goal, and that it would be

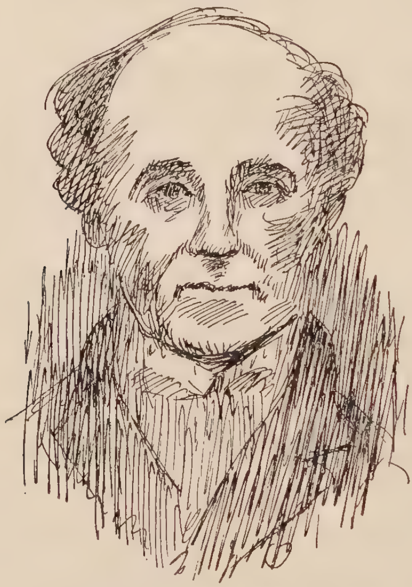

Fig. 54.—F. W. A. Argelander (1799-1875). (Pen sketch after photo by Augustin Rischgitz.)

laudable and expedient to confer on him the gold medal of the society.

The address on the occasion of the conferring of this well-merited honor was made by Sir John Herschel himself, and this address also takes place in the archives of astronomy, among classical documents, because it details with astonishing clearness

—considering the technicalities of the subject—the method that Bessel had used and the precise character of his accomplishment.

At the same time, with singular tact and felicity, reference is made to the efforts, apparently both successful, of two other investigators who almost simultaneously, or indeed just in advance of the German astronomer, had attained similar goals.

Three Friendly Rivals

The two other star-gazers in question were the distinguished Russian, Friedrich Georg Wilhelm Struve, and the Englishman Thomas Henderson.

It appeared that the last named astronomer, observing at the Cape of Good Hope, had been the very earliest of the three to measure a star-parallax, and that the Russian's apparently successful effort slightly antedated the conclusion of Bessel's series of observations.

Moreover, time was to show that the results of both Henderson and Struve were valid, so that the English astronomer stands as the first man in the world to attain success in a star-measurement so exquisitely delicate as to have come to be regarded by many practical astronomers as unattainable.

That Bessel should have been awarded the medal of the Royal Astronomical Society, while these amicable rivals received only honorable mention, was explained by the spokesman for the donors of the trophy and fully justified. The ground for this decision was that Bessel's measurement was of so convincing a character as to leave scarcely a possibility of doubt that it represented an apparent shift of a star's position not otherwise explicable than as true parallax.

That is to say, a shift due to the orbital change of the earth's position, and not to any one of the remaining possible causes.

It will interest the layman, and give a realizing sense of the

A "Brief" Three-Year Period of Testing

difficulties involved in the investigation, to note that Herschel states, as the only thing that can "possibly be cavilled at is the shortness of the period embraced by the observation—namely from August, 1837 to the end of March, 1840."

Something less than three years of continuous effort—the observations commonly repeated, as Bessel himself reported, sixteen times every night—seemed a short time in which to note and verify the oscillations of the star, though the shift of apparent position searched for is due solely to the change in position of the earth, which of course makes the full circle in a single year.

Herschel goes on to explain, however, that even the "brief" three-year period admits of five intersections of each curve with its axis, and of two maxima and two minima in the excursions on either side, gives ample room for testing a curve representing the observed shift of the star with theoretically true parallactic curves. "Under such circumstances," he continues, "it is quite out of the question to declare the whole phenomenon an accident or an illusion. Something has assuredly been discovered, and if that something be not parallax, we are altogether at fault and know not what other cause to ascribe it to."

Many Motions of the Earth

Such is the language of scientific caution.

To the uninitiated, the implications of the comment are clear only when it is recalled that there are various other apparent shifts of position of a star under such critical examination, due to the fact that our earth is progressing through space in a course far more complex than consideration of its orbital swing alone would suggest.

A moment's reflection will make the conditions clear, at least as to their general terms.

Plate XIV: Friedrich Wilhelm Bessel (1784-1846)
(Crow-quill interpretation of engraving in Williams' *History of Science*. Original source untraced)

Obviously the observer who looks through the telescope is moving eastward, with the rotation of the earth, at a rate sufficient to carry him round the world in twenty-four hours—that is to say with a speed varying from 1000 miles an hour at the equator to half that rate at the sixtieth parallel of latitude.

Secondly, the earth is rushing forward in the great circuit of its orbit at the rate of about 19 miles per second.

In the third place, the earth, with the entire solar system, is moving at the rate of something over 12 miles a second in the general direction of the bright star Vega in the sky of the north polar region.

If you attempt mentally to envisage these three motions of translation, combining them into a curve to represent the actual line of movement in space, an impression is gained of a vague tortuous spiral—a sort of corkscrew course—through the confines of space, which assuredly require the attention of a skilled mathematician for its accurate charting.

But that is by no means the end.

We must recall that by virtue of the earth's movement and the fact that the transition of light is not instantaneous, there are the phenomena of aberration of light (Bradley's discovery will be recalled), to be dealt with. Also the phenomena of nutation, because of that never-ending nodding of the earth's axis as it swings in the great circle which results in the far slower but not altogether negligible shift called precession, which is further accompanied by a minute change in the obliquity of the elliptic.

If we are to take into account all these movements, assuredly the problem becomes complex almost beyond solving.

Not so for an astronomer, however. In particular, not so for

Bessel, since he it is who has applied keen mathematical insight to the solving of these precise puzzles—and in so doing has taught his confrères how to interpret more accurately the star-charts of earlier observers, including the notable one of Bradley himself.

Varied Motions of the Stars

But there are still other possible complications that must be considered, originating at the other end of the line, as it were. There is the possibility that the stars under observation, in addition to the shifts of apparent position due to the causes just outlined, have also actual motions of their own.

Indeed, it is certain that there is actual motion in the case of the chief object to be observed, which is known as 61 Cygni (number 61 in the constellation Cygnus), because this is a double star, the components of which are necessarily revolving about a common center.

The revolution is so exceedingly slow that it seems negligible. But no possible movement can be entirely ignored when a residual movement so exceedingly minute as the possible parallax of the star is being searched for.

As to the two other stars, designated merely "a" and "b," which serve as fixed points of reference (one lying in direct line of the axis of 61 Cygni's two components, and the other at right angles), they are believed to be vastly more distant, and therefore less subject to apparent shift of position from any cause.

Yet the fact cannot be ignored that either one or both may have an actual motion of its own, across the line of sight, of sufficient magnitude to introduce a disturbing element in the measurements.

And now perhaps we understand why, in attempting to determine the parallax of 61 Cygni, it was not sufficient to make

Difficulties Overcome

accurate measurement of the relation of that double star to the two neighboring stars on a certain night, and to repeat the observation on another night six months later—and then to assume that any difference between the two measurements represents the parallax of 61 Cygni.

We begin to understand why it was necessary to make observations night after night, and even sixteen times every night, and to continue this series week after week and month after month.

And why, in the end, having made meticulous comparison of the measurements of each and every observation of all the thousands, it should seem to that other practical star-gazer, Herschel, that perhaps the series was rather small, covering a total period of less than three years (the total number of nights being, say, 940, and the aggregate observations numbering only 15,000) to give data for comparison adequate to prevent possible "cavilling."

Yet we must recall that Herschel himself did not cavil. On the contrary, he declared unequivocally that a definite phenomenon of star-movement (that is to say, apparent movement) had been revealed, which could not be accounted for by any and all of the disturbing factors that have just been outlined—wherefore it must be assumed that a certain residual movement is to be interpreted as actual parallax.

The amount of this residual movement, it is noted, is less than one-third of a second of arc—thirty one-hundredths of a second to be exact (and if ever one is to be exact, here certainly is the place for it).

The interpretation of this infinitesimal parallax—which represents the angles subtended by the semi-diameter of the earth's

orbit as viewed from the star—gives the distance of the star from the terrestrial observer.

It is 670,000 times the distance of the sun.

"Such," said Herschel, "is the universe in which we exist, and which we have at length found the means to subject to measurement, at least in one of its members, probably nearer to us than the rest."

What the Achievement Meant

To appreciate the note of exultation in that pronouncement, and to endeavor to appreciate the wonderment with which the pronouncement was doubtless received, we must recall that this verdict, given in the year 1841, was the first official recognition of the observation of the parallax of a star as a fact accomplished.

For the first time in the history of the world the distance of a star had been actually measured.

For the first time the hither confines of the stellar universe had been sounded.

For the first time could the distance of any star be stated in terms of measurement and not of mere conjecture.

The elder Herschel, father to the almost equally distinguished astronomer who now voiced the verdict of his official confréres, had made conjectures as to the depth of the galactic system that remain to this day astonishing approximations.

But these were confessedly only inspired guesses.

There was no guesswork involved in the interpretation of the thousands of observations that led to Bessel's parallactic determination. These were measurements made with delicacy that would have been impossible in an earlier generation, because they lacked the extraordinary heliometer-lens (a bisected lens, the two halves sliding past each other) of the great optician Fraunhofer.

Lacking that aid, even the keen-eyed Bessel could not have discriminated with sufficient accuracy to give data from which that residual thirty one-hundredths of a second of arc could be sifted out.

Dark Stars Discovered

It was the same instrument that revealed to Bessel certain movements of numerous other stars, not to be accounted for as parallax or by any of the other vagaries of movement, but which were interpreted as oscillations, proving that an invisible companion star was revolving in an orbit with the visible one,—which thus was revealed as a member of a binary system.

These observations being confirmed, and similar observations made of the like oscillations of other stars, it was for the first time revealed to the world that there are dark stars no less than bright ones in the stellar system.

Some of these "dark" stars were subsequently to be revealed, under higher powers of the telescope, as in reality bright, but too small to be visible through ordinary telescopes, or so near their primaries as to be quenched in the dazzling brightness of the larger body. Such proved to be the case, with the hypothetical companion of the brilliant Sirius, predicted by Bessel, but first seen a good many years later by the American optician Alvan Clark, who had pointed a new telescope at Sirius, partly to test the optical qualities of the lens.

We shall hear something more of this companion of Sirius, which was to become famous at a later day as the type of "white dwarf" star.

There are many others of the binary systems, however, in which the invisible companion star is unrevealed by the most powerful modern telescopes. And it is quite appropriate that this aspect of sidereal astronomy, as first revealed by the keen ob-

servations of Bessel, should be spoken of as the astronomy of the invisible.

At a later day, the spectroscope was to show that the census of double stars is enormous.

Throughout antiquity and until the time of Herschel, it was never suspected that stars exist in actual pairs. At all events the early users of the telescopes, who had come fully to recognize that the universe has depth as well as breadth, regarded the apparent proximity of pairs of stars as an accidental optical effect, one member of the seeming doublet being supposed to be far more distant than the other. But later observation revealed that, when viewed telescopically, one star in nine of all the naked-eye stars is a visual doublet, or binary; and that when spectroscopic doubles are added, a full third of all naked-eye stars (that is to say, of the total starry firmament of pre-telescopic days) are binaries.

Thus the astronomy of the invisible is found to be comparable in importance to the astronomy of the visible. The heavens teem with revolving systems, each of which may be regarded as an object lesson in truth at once of the Copernican system and of the law of universal gravitation.

Had there been skeptics remaining at the middle of the 19th century to challenge the truth of either thesis, the parallax studies and the opening up of the astronomy of the invisible would have given them adequate answer.

Star Distances Illustrated

A concluding word as to the astounding magnitude of the star-distances now first definitely revealed.

It is needless to repeat that these distances are quite beyond comprehension. Yet one cannot avoid seeking illustrations that will serve to give them at least a measure of tangibility. Here is

one of the many suggestions that at one time or another I have found useful in presenting the subject to a popular audience.

The distance of the nearest star, Alpha Centauri (the brightest star in the constellation of the Centaur), which was the star measured by Henderson, may be roughly stated as twenty-six trillion miles—26,000,000,000,000.

It does not help us much to note that this distance is equivalent to a billion trips around the globe at the equator. But suppose we try, in imagination, to make a demonstration in which we use a few million carloads of rolls of surgeons' plaster, each roll a wheel two inches wide and big enough to hold 12,000 miles of plaster.

Each roll, then, will enable us to put a strip of plaster from pole to pole across the zones,—a strip of plaster stretching like a meridian up and down the cheek of the world, as a surgeon might start to bandage the swollen face of a patient.

This strip, extending from pole to pole is, be it recalled, only two inches wide. Now I purpose to put beside it another strip, slightly over-lapping, and then another and another, with the intent to bandage thus piecemeal the entire globe.

We shall need no fewer than two billion rolls of plaster like the first. But fortunately that is the supply provided by the length of strips that in the aggregate would reach to the star.

With this supply available, we have only to add strip to strip, each slightly overlapping, and if we persist long enough, until the last roll is manipulated, we shall have covered the entire surface of the globe with a solid sheath of surgeon's plaster.

And as we contemplate our big patient thus encased in two-inch strips—two billion of them each 12,000 miles in length—

we perhaps gain a somewhat more tangible conception of the distance of a star than mere words can convey.

And this be it remembered, is the *nearest* star. The next nearest are two or three times as far away. It is computed that the average distance of the first magnitude stars is to be measured not in mere trillions but in scores of quadrillions of miles, and that the average eighth magnitude star is twenty times even that ridiculous distance.

If we were to bandage the earth on the basis of the distances of these stars, we should have not merely one layer of plaster, but thousands of layers.

And eighth magnitude stars, of course, are only in the midground of the sidereal picture. The stars that are really distant are the fifteenth or twentieth magnitude. One can hardly hope to find an illustration that would make their distances even vaguely tangible.

The astronomer resorts to light-years (or to "parsecs" of three and a quarter light-years each) and treats these units with entire familiarity. After all, as Professor Holden remarks, the distance represented by 600 light-years—or 6000 or 6,000,000—is no more inconceivable, properly speaking, than the distance represented by a single light year.

The real marvel of it is that a mere human being on our dust-speck planet could ogle a star through his telescope, and actually measure—measure, not guess at—distances that are meaningless from their very magnitude.

One recalls the oft-quoted words of Laplace:

"Contemplated as a whole, astronomy is the most beautiful monument of the human mind, the noblest record of its intelligence."

XXII

ADAMS—LEVERRIER—DARWIN—COMPLETING THE SOLAR SYSTEM

On July 3rd, 1841, a young undergraduate of St. John's College, Cambridge, wrote a memorandum which is now preserved among the well-nigh sacred mementos of the college library. The name of the young man, who was to graduate as Senior Wrangler two years later, was John Couch Adams.

What he wrote was this:

"Formed a design, at the beginning of this week, of investigating as soon as possible after taking my degree the irregularities in the motion of Uranus which are yet unaccounted for, in order to find whether they may be attributed to the action of an undiscovered planet beyond it; and if possible, thence to determine the elements of its orbit, etc., approximately, which would probably lead to its discovery."

After his graduation, the young mathematician did not forget his project.

On the contrary, he set to work rather promptly and worked assiduously, so that two years later he was able to communicate the results of his calculation to Prof. Challis, director of the Cambridge Observatory. The calculations were based on minute differences by which Uranus was observed to depart from the orbit predicted as normal for that planet.

Of course the disturbing influence of Jupiter and Saturn on the outer planet had been accounted for.

There remained a residual disturbance which could only be

explained by the supposition that there must be an exterior planet to exert a gravitational influence.

Location of this planet was, as Adams had stated, the problem he set himself.

When you reflect that Uranus, whose trifling departure from schedule was in question, is a planet so distant from the earth

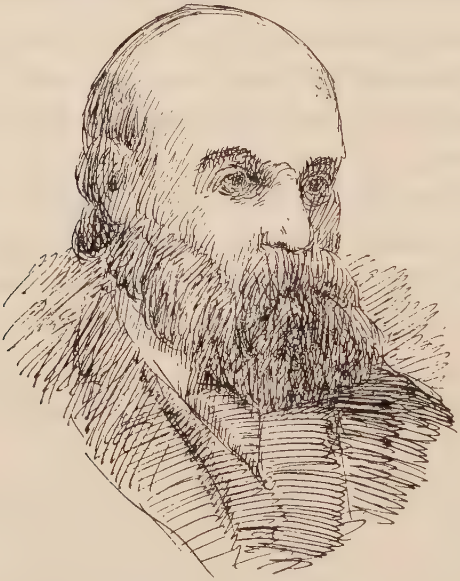

FIG. 55.—John Couch Adams (1819-1892). (Adapted from Hutchinson's *Splendour of the Heavens*. Macmillan Co. credited.)

that it is almost always invisible to the naked eye, ranking only as a faint telescopic star, the project might seem utopian.

The orbit of Uranus has a mean radius of more than one and three-quarters billion miles.

It is so far away that if you draw a chart of the solar system to scale, with one inch for the distance between the sun

and the earth Uranus at nearest is eighteen inches from the earth.

Light, traveling 186,000 miles per second, coming to us from the sun in eight minutes, requires two and a half hours to reach the orbit of our far-flung sister planet.

The Unseen Planet Located Mathematically

But distances mean nothing to the mathematicians, and Newton's law of gravitation applies to a planet of billion-mile radius precisely as it applies to little Mercury, or to the moon, or to a falling apple.

This is not to suggest that Adams' task was a simple one. It involved intricate calculations, else it would not have called for months of patient application. But one does not graduate Senior Wrangler at Cambridge without being a notable mathematician, so perhaps it was not altogether surprising (though it certainly does *seem* surprising on any basis), that the young man's calculation was accurate, and led to the correct answer.

At the point his figures indicated, located at so many degrees of Right Ascension and Declination, so localized that a telescope directed to that point could readily detect it, was the planet, lying yet another billion miles beyond the orbit of Uranus, which had exercised the disturbing influence by tugging at the gravitational lines which are like invisible cables connecting every body with every other body in the universe.

We know that this hypothetical planet was there, because Professor Challis directed his telescope to this part of the heavens and on two occasions, at an interval of eight days, detected there a "star" which was afterward known to be not a veritable star, but the planet for which he was looking.

But this observation, regrettable to say, did not constitute discovery of the planet.

Success That Was Failure

For it appears that Challis had no chart of that particular part of the heavens, and hence was obliged to make successive observations in order that by comparing the charts thus made, he could determine whether any one of the stars within the field of vision had changed position.

It must be recalled that this was before the day of celestial photography, and that the observations were therefore of necessity made somewhat laboriously.

Nevertheless the director of the observatory did make the observation, and had he not been unduly leisurely in comparing his two charts, he might perhaps have detected the slight but appreciable shift in position of one of his "stars,"—and the triumphant discovery would have been his reward.

It was a regrettable, even if comprehensible, tardiness of action. But perhaps the observer may be excused, if not justified, by the fact that Sir George Airy, the Astronomer Royal of England, to whom the calculation of Adams had been submitted by Prof. Challis had been even more leisurely of action. He had allowed the precious document to rest in a pigeon-hole of his desk (or in some equally unprocreative location) for the best part of a year before returning it to the Cambridge astronomer with the suggestion that it might be worth while to make a search for the suppositious planet to which the calculations pointed.

The net result, then, was that the telescopic sky-sweep that revealed the planet masking as a star to the observer was made on August 4th and August 12th of the year 1846—almost a twelve-month after the young calculator had submitted the results of his mathematical toil for consideration.

An thereby hangs a tale which, for young John Couch Adams, spelled tragedy.

Another Mathematician on the Trail

For it chanced that over across the channel, in France, another mathematician, not this time a tyro but a man of recognized authority, had been ardently pursuing the same quest—neither calculator knowing of the work of the other.

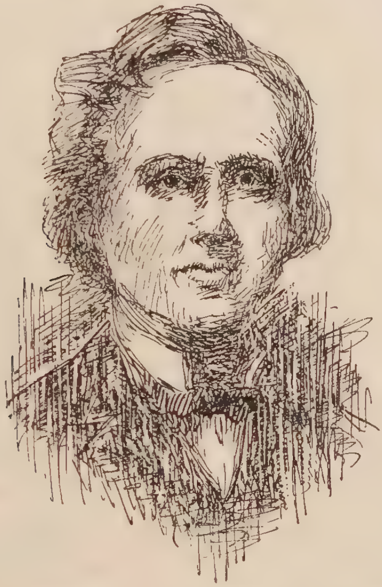

FIG. 56.—U. J. J. Leverrier (1811-1877). (Adapted from photo of statue.)

This Frenchman, Urbain Jean Joseph Leverrier had finished his calculations, and communicated them to the French Academy on August 31st, 1846—four weeks lacking a day, as it chanced, from the occasion when Prof. Challis, over at Cambridge, had actually seen—but had not recognized—the object which this second mathematician had not run to cover with pencil and figures.

And during that term of weeks—perhaps because it was the holiday season, perhaps because he was not greatly interested—the Cambridge astronomer had not taken the trouble to compare his observations, and therefore had lost the prize that was fairly within his grasp.

By his procrastination, he had withheld from young Adams the just reward that should have crowned his brilliant effort.

Yet for another term of three weeks fate hung in the balance, for it was not until September 23rd that the letter which the French mathematician had sent to Dr. Galle of the Berlin Observatory, reached its destination.

Leverrier Wins

Then the die was cast. No longer was it possible that the procrastinator of Cambridge should retrieve his error.

For the German astronomer lost no time whatsoever in turning his telescope on the stars at the point indicated by Leverrier's calculations.

That very night he saw what looked to be a star in a position where no star appeared on a recently published chart of that part of the heavens. The next night it was seen that the suspected object had clearly shifted its position.

Eureka! The far-flung planet, to be known in future as Neptune, had been discovered.

The diameter of the solar system had been expanded by another billion miles; the area of the plane of its planetary orbits, more than doubled.

History does not record how the director of the Cambridge Observatory and the Astronomer Royal of England felt, nor what, if anything printable, young Adams said.

Except, indeed, that the young mathematician a few months later communicated a brief statement of his connection with the

discovery to the Royal Astronomical Society, in which he gracefully acknowledges M. Leverrier's just claims to the honors of the discovery.

"For there is no doubt that his researches were first published to the world, and led to the actual discovery of the planet by Dr. Galle, so that the facts stated above cannot detract, in the slightest degree, from the credit due to M. Leverrier."

The "facts stated above" are merely an altogether modest epitome of Adams' own efforts, and an acknowledgement of the "kind intervention of Prof. Challis," and the "kindest possible manner" of the Astronomer Royal in supplying data regarding Uranus that had been utilized in his calculations. Nothing whatever is said about any delay in the search for the planet. Nor is it even stated, though it might justly have been stated, that the earlier computation of Adams which so barely missed success, differed by less than 2½ degrees from the position where the planet was found—a position, it may be added, within 47 seconds of a mean of the locations ascribed by the two calculations.

But, despite the young mathematician's explicable reticence, all the world knew the story, and the names of the English and the French mathematicians are always coupled when the discovery of Neptune is referred to.

A weird, almost fantastic achievement, the discovery has always seemed in the popular view.

It is pleasant to record that the young mathematician who failed through no fault of his own, in time succeeded to the position of Professor of Astronomy and Chief of the Observatory at Cambridge; and that to this day the holder of a certain official position at the University is known as the John Couch Adams astronomer.

The Completed Solar System

With the discovery of Neptune, the roster of the sun's major planetary family was, for the nineteenth century, complete.

The French discoverer of Neptune did, indeed, calculate an orbit for an interior planet, suspected to exist because of perturbation of Mercury, but though prematurely christened Vulcan, this hypothetical nurseling of the sun still haunts the realm of the undiscovered. Meantime a much-discussed hypothetical trans-Neptunian planet, whose existence had been suggested by certain

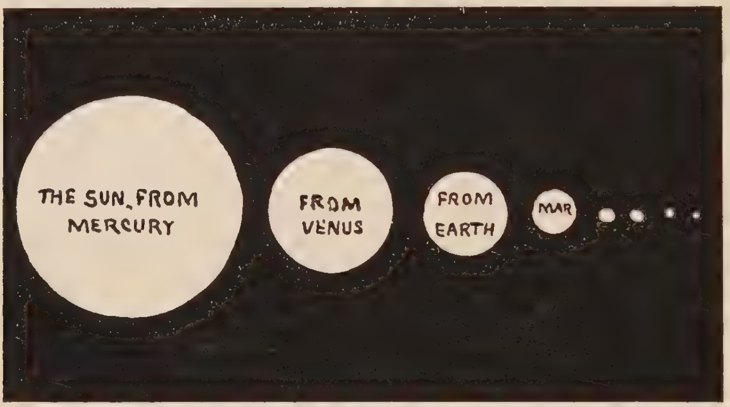

Fig. 57.—Relative Apparent Size of the Sun from Different Planets. The planets not named are, in sequence, Jupiter, Saturn, Uranus, and Neptune.

"residual perturbations" of Uranus, and by the movements of comets, remained equally unrevealed until the year 1930.

As to the perturbations of Mercury, it may be said in passing that these are associated with the rate of swing of the apsides (the major axis of the elliptical orbit) which is now accounted for, to the satisfaction of many (but by no means all) astronomers, by application of the Einstein theory of Relativity.

The discovery of a trans-Neptunian planet in 1930 by the American astronomers at the Lowell Observatory will be referred

Plate XV: John Herschel (1792-1871)
(Pencil interpretation of half-tone in Abbot's *The Earth and the Stars*.
Original source said to be a photo by J. M. Cameron)

to more at length later. Here we are concerned with the solar system as known to the generation that witnessed the discovery of Neptune.

So vast is the orbit of Neptune that its circuit of the sun takes 164 years. That is to say, a round of the seasons on that planet is equivalent to 164 years on the earth.

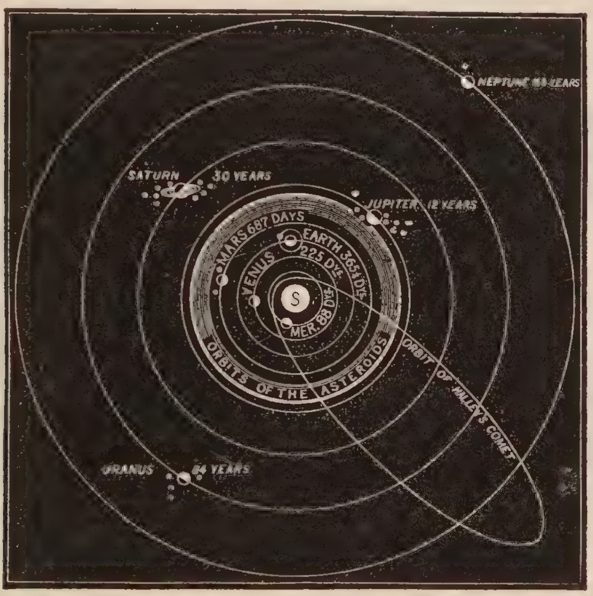

FIG. 58.—The Solar System and Halley's Comet. (Slightly modified from Morgan's *Advanced Physiography*.)

To an inhabitant of Neptune (and if such there were) the sun would seem no larger than Venus seems to us when at her nearest—though almost infinitely more brilliant. The earth and Mars would be hopelessly invisible, unless with a powerful telescope and by screening off the light of the sun. Jupiter would be seen somewhat as we see Mercury. Saturn would be fairly conspicuous.

But only Uranus among all the planets would be better seen from Neptune than from the earth.

Still considering the solar system as known in the 19th century, it may be of interest to give a tangible illustration, showing the relative sizes and distances of the planets. Such an illustration was given by Sir John Herschel as follows:

A Model of the Solar System

"Choose any well-levelled field. On it place a globe two feet in diameter. This will represent the sun; Mercury will be repre-

FIG. 59.—Relative Sizes of the Planets. The planets not labeled are, in sequence, the Earth, Venus, Mars and Mercury.

sented by a *grain of mustard-seed* on the circumference of a circle 164 feet in diameter for its orbit; Venus, a *pea* on a circle of 284 feet in diameter; the Earth also a *pea* on a circle of 430 feet; Mars, a rather large *pin's-head* on a circle of 654 feet; the asteroids, *grains of sand* in orbits of 1000 to 1200 feet; Jupiter, a *moderate-sized* orange in a circle nearly half a mile across; Saturn, a *small orange* on a circle of four-fifths of a mile; Uranus, a *full-sized cherry* or *small plum* upon the circumference of a circle more than a mile and a half; and finally Neptune, a

good-sized plum on a circle about two miles and a half in diameter."

To which Prof. Young has added:

"On this scale the nearest *star* would be on the opposite side of the globe, at the antipodes, 8000 miles away."

Contrast that colossal mechanism of the new solar system with the mechanism of the old Ptolemaic system. The whole universe as the sagacious Greek, or as any other astronomer of antiquity, even including Aristarchus, conceived it, could be stored away almost anywhere in the present solar system, without interfering with the orderly progression of the circling globes.

The System of Satellites

Though no further additions to the company of major planets were to be made prior to 1930, there were numerous accessions to the subordinate system of the satellites.

With the advance of telescopic powers, moons appeared in attendance on various of the outlying planets, several of them so tiny as to test the power of all but the largest lenses or mirrors.

Of these the midget attendants of our Martian neighbor, discovered by Professor Hall with the great Washington refractor, are of greatest interest, because of their small size and extremely rapid flight. One of them is poised only 6000 miles from Mars, and whirls about him almost four times as fast as he revolves, seeming thus, as viewed by the hypothetical Martian, to rise in the west and set in the east, and making the month only one-fourth as long as the day.

Other planets have also received new moons, but Saturn in particular has been favored, until now it is known that this planet has ten of these attendants, in addition to its famous set of rings. Seven were known prior to the 19th century; the eighth was discovered by G. P. Bond and Lassell in 1848, a

ninth by W. H. Pickering in 1899, and a tenth by the same observer in 1905. The ninth planet, in time of discovery, is of so wide an orbit that its period of revolution is one and a half years, or more than six times that of Mercury round the sun.

FIG. 60.—The Planets in Sequence Against the Face of the Sun, to Show Relative Sizes. From left to right the planets are Mercury, Venus, Earth, Mars, Cluster of Asteroids, Jupiter, Saturn, Uranus, Neptune. Note the varying number of satellites.

Moreover, it has the anomalous habit of revolving in the retrograde direction—a strange particularity about which something will be said in another connection.

Meantime reference must be made to the discovery of the inner or crape ring of Saturn, which was made simultaneously in 1850 by William C. Bond, at the Harvard Observatory, in America, and the Reverend W. R. Dawes in England.

Our most important advances in knowledge of Saturn's unique system are due to the mathematician.

Laplace, like his predecessors, supposed these rings to be solid, and explained their stability as due to certain irregularities of contour which Herschel had pointed out. But about 1851 Professor Peirce, of Harvard, showed the untenability of this conclusion, proving that were the rings as Laplace thought them they must fall of their own weight.

Fig. 61.—Saturn and His Rings. (Adapted from photo by Dr. E. C. Slipher.) The inner ring is the "crape ring."

Then Professor J. Clerk-Maxwell, of Cambridge, took the matter in hand, and his analysis reduced the puzzling rings to a cloud of meteoric particles—a "shower of brick-bats"—each fragment of which circulates exactly as if it were an independent planet, though of course perturbed and jostled more or less by its fellows.

Mutual perturbations—and the disturbing pulls of Saturn's orthodox satellites, as investigated by Maxwell, explain nearly all the phenomena of the rings in a manner highly satisfactory.

But perhaps the most interesting accomplishments of mathe-

matical astronomy since the time of Adams and Leverrier are those that refer to the earth's own satellite.

Sir George Darwin and the Moon

That seemingly staid body was long ago discovered to have a propensity to gain a little on the earth, appearing at eclipses an infinitesimal moment ahead of time. Astronomers were sorely

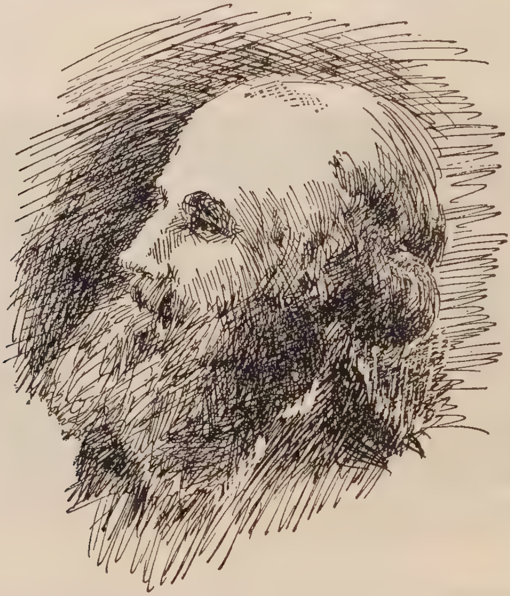

FIG. 62.—James Clerk Maxwell (1831-1879). (Adapted from half-tone in William's *Story of Nineteenth Century Science.*)

puzzled by this act of insubordination, but at last Laplace and Lagrange explained it as due to an oscillatory change in the earth's orbit, thus fully exonerating the moon, and seeming to demonstrate the absolute stability of our planetary system, which the moon's misbehavior had appeared to threaten.

This highly satisfactory conclusion was an orthodox belief of celestial mechanics until 1853, when Adams of Neptunian fame,

with whom complex analyses were a pastime, reviewed Laplace's calculation, and discovered an error which, when corrected, left about half the moon's acceleration unaccounted for. This was a momentous discrepancy, which at first no one could explain. But presently Helmholtz, the great German physicist, suggested that a key might be found in tidal friction, which, acting as a

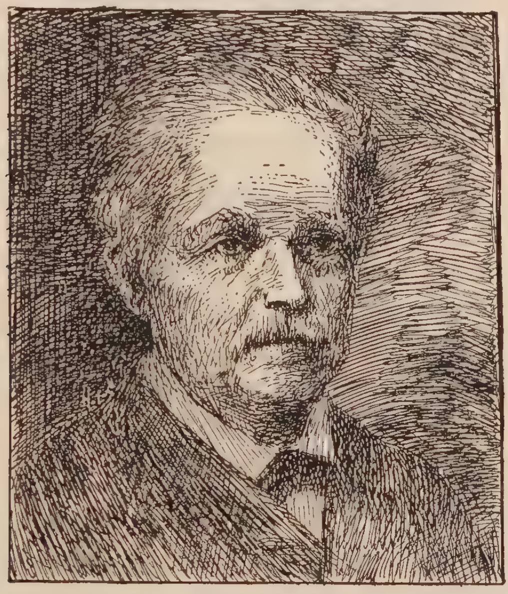

Fig. 63.—H. L. F. von Helmholtz (1821-1894). (Redrawn from engraving in Williams' *Story of Nineteenth Century Science.*)

perpetual brake on the earth's rotation, and affecting not merely the waters but the entire substance of our planet, must in the long sweep of time have changed its rate of rotation.

Thus the seeming acceleration of the moon might be accounted for as actual retardation of the earth's rotation—a lengthening of the day instead of a shortening of the month.

Again the earth was shown to be at fault, but this time the

moon could not be exonerated, while the estimated stability of our system instead of being re-established, was quite upset.

For the tidal retardation is not an oscillatory change which will presently correct itself, like the orbital wobble, but a perpetual change, acting always in one direction.

FIG. 64.—Sir George H. Darwin (1845-1912). (Based on half-tone in Shapley and Howarth's *Source Book in Astronomy.* Original not traced.)

Unless fully counteracted by some opposing reaction, therefore (as it seems not to be), the effect must be cumulative, the ultimate consequences disastrous.

The exact character of these consequences was first estimated by Professor G. H. Darwin (afterward Sir George), son of the immortal Charles, in 1879. He showed that tidal friction, in retarding the earth, must also push the moon out from the parent planet on a spiral orbit.

The Birth of the Moon

Plainly, then, the moon must formerly have been nearer the earth than at present. At some very remote period it must have actually touched the earth; must, in other words, have been thrown off from the then plastic mass of the earth, as a polyp buds out from its parent polyp.

At that time the earth was spinning about in a day of from two to four hours.

Now the day has been lengthened to twenty-four hours, and the moon has been thrust out to a distance of a quarter-million miles.

But the end is not yet.

The same progress of events must continue, till, at some remote period in the future, the day has come to equal the month, lunar tidal action has ceased, and one face of the earth looks out always at the moon with that same fixed stare which even now the moon has been brought to assume towards her parent orb.

Should we choose to take even greater liberties with the future, it may be made to appear (though some astronomers dissent from this prediction) that, as solar tidal action still continues, the day must finally exceed the month, and lengthen out little by little towards coincidence with the year; and that the moon meantime must pause in its outward flight, and come swinging back on a descending spiral, until finally, after the lapse of untold aeons, coming within "Roche's limit" (about 10,000 miles), it is explosively disrupted—with what consequences to our own planet may be imagined.

But even though imagination pause far short of this direful culmination, it still is clear that modern calculations, based on

inexorable tidal friction, suffice to revolutionize the views formerly current as to the stability of the planetary system.

The eighteenth-century mathematician looked upon this system as a vast celestial machine which had been in existence about six thousand years, and which was destined to run on forever.

The analyst of a later day computes both the past and the future of this system in millions instead of thousands of years, yet feels well assured that the solar system offers no contradiction to those laws of growth and decay which seem everywhere to represent the immutable order of nature.

Vagabonds of the Solar System

Until the mathematician ferreted out the secret, it surely never could have been suspected by any one that the earth's serene attendant,

> "That orbed maiden, with white fire laden,
> Whom mortals call the moon,"

could be plotting injury to her parent orb. But there is another inhabitant of the skies whose purposes have not been similarly free from popular suspicion.

Needless to say I refer to the black sheep of the sidereal family, that "celestial vagabond" the comet.

Time out of mind these wanderers have been supposed to presage war, famine, pestilence, perhaps the destruction of the world.

And little wonder. Here is a body which comes flashing out of boundless space into our system, shooting out a pyrotechnic tail some hundreds of millions of miles in length; whirling, perhaps, through the very atmosphere of the sun at a speed of three or four hundred miles a second; then darting off on a hyperbolic orbit that forbids it ever to return, or an elliptical one that cannot be closed for hundreds or thousands of years; the tail mean-

time pointing always away from the sun and fading to nothingness as the weird voyager recedes into the spatial void whence it came.

Not many times need the advent of such an apparition coincide with the outbreak of a pestilence or the death of a Caesar to stamp the race of comets as an ominous clan in the minds of all superstitious generations.

It is true, a hard blow was struck at the prestige of these alleged supernatural agents when Newton proved that the great comet of 1680 obeyed Kepler's laws in its flight about the sun; and an even harder one when the same visitant came back in 1758, obedient to Halley's prediction, after its three-quarters of a century of voyaging out in the abyss of space. Proved thus to bow to natural law, the celestial messenger could no longer fully sustain its rôle. But long-standing notoriety cannot be lived down in a day, and the comet, though proved a "natural" object, was still regarded as a very menacing one for another hundred years or so.

It remained for the nineteenth century completely to unmask the pretender and show how egregiously our forebears had been deceived.

The unmasking began early in the century, when Dr. Olbers, then the highest authority on the subject, expressed the opinion that the spectacular tail, which had all along been the comet's chief stock-in-trade as an earth-threatener, is in reality composed of the most filmy vapors, repelled from the cometary body by the sun, presumably through electrical action, with a velocity comparable to that of light.

This luminous suggestion was held more or less in abeyance for half a century.

Then it was elaborated by Zollner, and particularly by Bredichin, of the Moscow Observatory, into what has since been regarded as the most plausible of cometary theories.

It is held that comets and the sun are similarly electrified, and thence mutually repulsive. Gravitation vastly outmatches this repulsion in the body of the comet, but yields to it in the case of gases, because electrical force varies with the surface, while gravitation varies only with the mass. From study of atomic

Fig. 65.—A Typical Comet. (Adapted from a photograph of Brooks' Comet of 1910. Origin not traced.)

weights and estimates of the velocity of thrust of cometary tails, Bredichin concluded that the chief components of the various kinds of tails are hydrogen, hydrocarbons, and the vapor of iron; and spectroscopic analysis goes far towards sustaining these assumptions.

The Comet's Phantom Tail

But, theories aside, the unsubstantialness of the comet's tail has been put to a conclusive test. Twice during the nineteenth century the earth has actually plunged directly through one of these threatening appendages—in 1819, and again in 1861, once being immersed to a depth of some three hundred thousand miles

in its substance. Yet nothing dreadful happened to us. There was a peculiar glow in the atmosphere, so the more imaginative observers thought, and that was all.

After such fiascos the cometary train could never again pose as a world-destroyer.

But the full measure of the comet's humiliation is not yet told. The pyrotechnic tail, composed as it is of portions of the comet's actual substance, is tribute paid the sun, and can never be recovered. Should the obeisance to the sun be many times repeated, the train-forming material will be exhausted, and the comet's chiefest glory will have departed. Such a fate has actually befallen a multitude of comets which Jupiter and the other outlying planets have dragged into our system and helped the sun to hold captive here.

Many of these tailless comets were known to the 18th century astronomers, but no one at that time suspected the true meaning of their condition.

It was not even known how closely some of them are enchained until the German astronomer Encke, in 1822, showed that one which he had rediscovered, and which has since borne his name, was moving in an orbit so contracted that it must complete its circuit in about three and a half years.

Shortly afterwards another comet, revolving in a period of about six years, was discovered by Biela, and given his name.

Only two more of these short-period comets were discovered during the first half of last century, but latterly they have been shown to be a numerous family. About thirty are known which the giant Jupiter holds so close that the utmost reach of their elliptical tether does not let them go beyond the orbit of Saturn.

These aforetime wanderers have adapted themselves wonder-

fully to planetary customs, for all of them revolve in the same direction with the planets, and in planes not wide of the ecliptic.

Checked in their proud hyperbolic sweep, made captive in a planetary net, deprived of their trains, these quondam free-lances of the heavens are now mere shadows of their former selves. Considered as to mere bulk, they are very substantial shadows, their extent being measured in hundreds of thousands of miles; but their actual mass is so slight that they are quite at the mercy of the gravitation pulls of their captors.

And worse is in store for them. So persistently do sun and planets tug at them that they are doomed presently to be torn to shreds.

From Comet to Meteor

Such a fate has already overtaken one of them, under the very eyes of the astronomers, within the relatively short period during which these ill-fated comets have been observed.

In 1832 Biela's comet passed quite near the earth, as astronomers measure distance, and in doing so created a panic on our planet. It did no greater harm than that, of course, and passed on its way as usual.

The very next time it came within telescopic hail it was seen to have broken into two fragments.

Six years later these fragments were separated by many millions of miles; and in 1859, when the comet was due again, astronomers looked for it in vain. It had been completely shattered.

What had become of the fragments? At that time no one positively knew.

But the question was to be answered presently. It chanced that just at this period astronomers were paying much attention to a class of bodies which they had hitherto somewhat neglected, the familiar shooting-stars, or meteors. The studies of Newton,

of Yale, and Adams, of Cambridge, with particular reference to the great meteor-shower of November, 1866, which Newton had predicted and shown to be recurrent at intervals of thirty-three years, showed that meteors are not mere sporadic swarms of matter flying at random, but exist in isolated swarms, and sweep about the sun in regular elliptical orbits.

FIG. 66.—G. V. Schiaparelli (1835-1910). (Crow-quilled from a half-tone of unstated origin in Shapley and Howarth's *Source Book in Astronomy.*)

Presently it was shown by the Italian astronomer Schiaparelli that one of these meteor swarms moves in the orbit of a previously observed comet, and other coincidences of the kind were soon forthcoming.

The conviction grew that meteor swarms are really the débris of comets; and this conviction became a practical certainty

when, in November, 1872, the earth crossed the orbit of the ill-starred Biela, and a shower of meteors came whizzing into our atmosphere in lieu of the lost comet.

And so at last the full secret was out.

The awe-inspiring comet, instead of being the planetary body it had all along been regarded, is really nothing more nor less than a great aggregation of meteoric particles, which have become clustered together out in space somewhere, and which by josting one another or through electric action become luminous. So widely are the individual particles separated that the cometary body as a whole has been estimated to be thousands of times less dense than the earth's atmosphere at sea-level.

Hence the ease with which the comet may be dismembered and its particles strung out into streaming swarms.

So thickly is the space we traverse strewn with this cometary dust that the earth sweeps up, according to Newcomb's estimate, a million tons of it each day.

Each individual particle, perhaps no larger than a millet seed, becomes a shooting star, or meteor, as it burns to vapor in the earth's upper atmosphere. And if one tiny planet sweeps up such masses of this cosmic matter, the amount of it in the entire stretch of our system must be beyond all estimate.

What a story it tells of the myriads of cometary victims that have fallen prey to the sun since first he stretched his planetary net across the heavens!

BOOK VI

THE NEW ASTRONOMY

"Why did not someone teach me the constellations, and make me at home in the starry heavens, which are always overhead?"

—*Carlyle.*

XXIII

FRAUNHOFER—KIRCHHOFF—HUGGINS—THE STARS BROUGHT TO EARTH

THE year 1859, and another epoch. When the time comes to reform the calendar, it will be well to use that date for the initial year of the new era. Then occurred what in the not distant future will be recognized as the most momentous event in human history—the publication of Darwin's *Origin of Species*.

By a breath-taking coincidence, the same year saw the stars virtually brought to earth and analyzed in the laboratory.

Now for the first time was revealed the unity of nature of every microscopic living cell of the organic world, and the unity of nature of every telescopic cell of the sidereal universe. At last a new scientific Revelation enabled man for the first time to envisage with a measure of clarity his true position in the cosmos.

With such landmarks available it must in the near future be recognised as a strange anachronism, to measure time and affairs from an event which augured the descent of civilization into a fog-bound valley of superstition, whereas the new date marks the attainment, after a long and painful struggle, of at least a minor peak whence regions can be scanned where there is light instead of darkness, where progress will no longer be obstructed by mythologic phantoms.

But we are here concerned not with prognostications for the new era, but with the record of that part of its achievement that concerns the new revelations in the field of astronomy.

A Necromantic Instrument

We shall see that it is an amazing record—unbelievable, did we not know it to be true.

In bringing the stars to earth out of the unimaginable depths of space, and wresting from them their inmost secrets, a thing was accomplished which the wisest men of but a single generation before had pronounced impossible—a thing, indeed, that was impossible, and still would be, but for the introduction of a new instrument of necromantic power; an instrument before which, even now, one pauses in wonderment, marveling whether the records of its accomplishment can be in truth actualities, and not mere phantasies from dreamland.

Yet there is no question as to the answer. The accomplishments of the spectroscope are valid, true, clearly demonstrable. This wonder-working instrument, more marvelous because of its extreme simplicity, performs its feats of jugglery in the open, and leaves no possible doubt in the mind of the observer either as to their validity or as to their meaning and interpretation.

Yet it must be recalled that the essential structure of this instrument—a simple prism of glass—was a familiar object in the physical laboratory, and had been searchingly investigated as to its possible uses, for more than two centuries before the man of genius appeared who could even *see* the alphabet of the message that awaited interpretation. Another generation elapsed before a yet keener-eyed man of genius began to decode the message. And yet another generation—indeed, almost a half century of time—had to elapse before a third man of genius saw the real import of the message, and envisaged the true possibilities of investigation of the nature of things that the message augured.

Our appreciation of the inspired insight of the men who finally

opened their eyes and mind to the cryptograph which the glass prism materializes from sunbeams is enhanced when we recall that the matchless Newton himself was the first and most sagacious student of the prismatic record, yet seems never to have even seen, much less interpreted, the script which is obvious to all eyes now that attention has been called to it.

The Secret of the Sunbeam

The script in question takes the form of lines, bright or dark as the case may be, that lie across the spread-out band of color of the familiar spectrum displayed when a beam of light is scattered by a glass prism.

The man who first saw the lines that Newton so regrettably overlooked was a distinguished English chemist and physicist of original genius, otherwise known for the discovery of the chemical elements palladium and rhodium, for the invention of the camera lucida and the goniometer (crystal-angle measurer), and for searching investigations in the field of electricity and optics which led him, among other things, to the discovery of ultraviolet rays that have gained so much fame in our own day.

His name was Wollaston. While inspecting the spectrum of a beam of light transmitted to the glass prism through a narrow slit, Wollaston saw, as no man had seen before him, a series of dark lines drawn, as if with a pen, at intervals across the band of the spectrum.

But beyond that his keen eyes for once failed him, and he made the critical mistake of interpreting the lines as being drawn to mark off or differentiate the different colors in the spectrum —whereas in reality the essential typicality of the lines is that they occur at definite locations within the various fields of the regularly distributed colors. The mistake threw him altogether

off the track, and was perhaps responsible for the entire unfruitfulness of his discovery.

Neither he nor anyone else at the time had the remotest inkling as to the significance of the dark lines—nor, perhaps, suspected that they were more than incidental appurtenances of the spectrum.

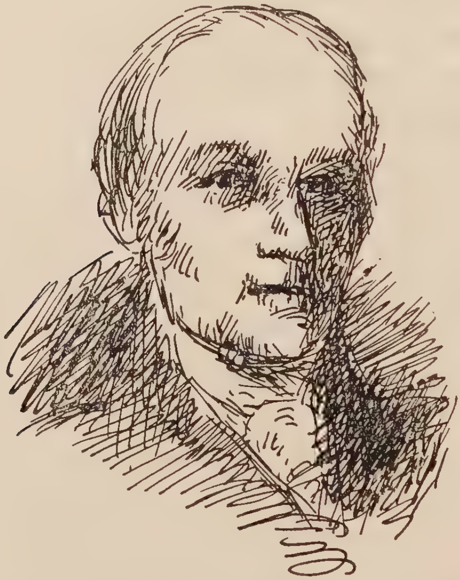

Fig. 67.—William Hyde Wollaston (1766-1828). (Adapted from half-tone in Williams' *Story of Nineteenth Century Science.*)

This was in the year 1792.

Twenty-three years later, in 1815, Joseph Fraunhofer, another creative genius of yet keener eye and more penetrating imagination studied the spectrum. And to him the dark lines in the outspread band of color yielded the first intimations of their secret.

Somewhat as the hieroglyphic carvings of the Rosetta stone

yielded, almost at the same time, the first intimation of *their* secret to Thomas Young.

Or as the first terms of the secret of the ether-wave nature of light itself were revealed through study of spectrum effects of another type by the same investigator.

The Genius of Fraunhofer

Joseph Fraunhofer, when he re-discovered the lines in the spectrum in the year 1815, was twenty-eight years of age.

He had already achieved fame as the perfector of the refracting telescope, and the inventor of the optical device, so important a little later in the field of the astronomy of precision, known as the heliometer.

He was a Bavarian by birth, and he spent his life, and died at the early age of thirty-nine, at Munich.

A frail, physically ill-developed man; crippled indeed from an early accident, in which he was partly buried under the ruins of a falling building. Incidentally, this accident, though it left him almost deformed, reacted in another way in his favor. His condition excited the sympathy of a wealthy passer-by who gave him a sum of money, which he used in part to pay for lodgings, and in part to purchase a book on optics—a book that furnished the foundation for his future professional activities.

The undernourished body of the impoverished orphaned youth never attained real maturity, or at least failed to attain normal ruggedness.

But there was no keener brain, no sharper eye, no more responsive mentality, no more dexterous hand, in all Europe than were the endowments of this young German optician. He made telescopes that were the pride of the great astronomers who were able to secure them. He invented optical instruments that made possible the discovery of star-parallax. He achieved im-

mortality by rediscovering the lines in the spectrum, and proving that they have a meaning well worth fathoming.

Fraunhofer made earnest and persistent effort to find out that meaning. He studied sunlight, moonlight, the light of Venus. He charted the lines in the spectrum, gave letters to certain groups in definite positions, which letters are still retained. He *knew* that here were secrets of profound significance, hidden in the sunbeams, and he never wavered in the attempt to clarify the mystery.

But death claimed him before he could fully decode the message, and the full solution had to wait the coming maturity of another German, this time a Prussian who, as it chances, was born two years before Fraunhofer died.

The Secret Revealed

The name of this third genius of our triumvirate is Gustav Robert Kirchhoff.

It was in the laboratory of the famous chemist, Robert Wilhelm Bunsen at Heidelberg, that Kirchhoff made the investigations, in collaboration with Bunsen himself, that were to eventuate in comprehension and demonstration of the meaning of the Fraunhofer lines in the spectrum.

The discovery came about through testing the light of many chemical substances rendered incandescent in the flame of the famous heater invented by the master of the laboratory, and known ultimately in every laboratory of the world as the Bunsen burner.

Soon it was seen that, of the long series of lines, variously distributed, that appear in the spectrum of the sun's light, direct or reflected, only certain groups, or even individual lines, appear when the light tested is of different origin. When sodium is

burned in the flame, for example, two lines in the location that Fraunhofer had marked D are particularly prominent.

Fraunhofer himself had observed that these particular lines were nearly always present in the light of terrestrial flames. But he had missed the secret of their interpretation—had failed to

Fig 68.—Gustav Robert Kirchhoff (1824-1887). (Adapted from half-tone in Williams' *Story of Nineteenth Century Science.*)

realize that here was the key to the code of symbols. And though a number of other imaginative physicists had studied the lines, no one of them more than half-guessed the truth.

But now, in the laboratory of Bunsen, and with the cooperation of that master, Kirchhoff began to realize the full meaning of what he saw.

Presently it was beyond cavil that certain lines in the spectrum are associated with certain definite chemical substances.

The two D lines, for example, are sodium lines.

Only when sodium is present are these lines present. They are present in the light of the sun, to be sure. But this only proves that there must be sodium in the sun!

That was half the secret. The other half was this: when sodium vapor colored the flame of the Bunsen burner, the sodium lines appeared as bright yellow lines in the spectrum—brilliant lines, still unobscured when ordinary sunlight was allowed to shine through the sodium flame upon the spectrum slit. But when an oxyhydrogen lime-light (which like the light of all incandescent solid or liquid bodies, gives a spectrum without dark lines) played on the flame, the spectrum of the sodium vapor in the flame no longer registered bright lines, but in their place, dark lines occupying the same position.

The Dark and Bright Lines Explained

"This phenomenon," said Kirchhoff, "is easily explained upon the supposition that the sodium flames absorb rays of the same degree of refrangability as those it emits, while it is perfectly transparent for all other rays."

That is to say, an incandescent vapor of a chemical substance, say sodium, gives a bright-line spectrum. The same vapor, when an excessively bright light shines through it, reveals the identity of the vaporized substance by showing dark lines instead of bright lines.

Both the bright and the dark D lines spell sodium; but in one case they tell of light coming directly from the incandescent sodium vapor itself, and in the other they tell of a brighter light shining through the vapor from some incandescent source on the other side.

Further interpreted, this means that the dark D lines in the solar spectrum reveal sodium as a vapor in the outer atmosphere

of the sun, through which bright light from the surface or interior of the sun is shining.

For convenience the bright-line spectrum came to be spoken of as the direct spectrum; the dark-line spectrum as the reversed spectrum. Kirchhoff and Bunsen were soon able to secure the reversing effect, as well as the direct effect, with vapors of potassium, strontium, calcium, and barium, by exploding mixtures of the chlorates of these metals and milk-sugar in front of the slit of the apparatus, while the direct solar rays fell on the instrument.

With wonderment they realized that here was a new method of chemical analysis, utterly different from anything hitherto conceived.

They saw that the reversed lines of the laboratory chemicals took the place of reversed lines of ordinary sunlight—each chemical having its individual stations.

It must have been with something approaching awe that they realized that there in their terrestrial laboratory at Heidelberg, they were subjecting the atmosphere of the sun to chemical analysis.

In effect, they had brought the sun into the laboratory.

The Fraunhofer lines were revealing to them knowledge of the sun's constitution such as had been hidden from all men; such as might well have been supposed to be beyond the reach of human investigation.

First of all men, they were able to make the astounding announcement that terrestrial elements can be demonstrated to be present in the sun.

Sun and planets were proved of one substance.

The scientific world heard the announcement, and stood aghast.

The Amazing Import of the Revelation

Not that the message was altogether unexpected. Imaginative men, ever since the day of old Anaxagoras back there in Greece, had guessed that the sun must be a fire ball of some earthly materials—perhaps of iron, since that metal was known to be a chief constituent of meteorites. Then of course the nebular hypothesis, the pretty generally accepted theory of cosmogony, made planets and sun alike residual structures from an original fire-mist.

On the other hand, the theory of Herschel had not been forgotten, according to which the sun is a habitable body, with only a shining mantle to give us heat and light. With such a thesis, the thought of a sun with an atmosphere of vaporized metals is obviously incompatible.

But in any event, regardless of preconception, how astounding, how almost unbelievable, that physical demonstration should be made—not guess work, but demonstration—of the chemical substance of a body more than 92,000,000 miles removed!

It had seemed wizardry to measure the distance of a star but here was yet more bewildering necromancy.

To reach out across the abysm, in effect pluck forth a ladle full of the solar substance, and subject it to an analysis! Unthinkable! yet coming from the laboratory of the famous Bunsen, the report must be believed. Wonders would never cease!

With the next move, the wonder grew.

An amateur astronomer, inspired by the new message, enthralled by its promise, hastened to secure a prism of glass and, after long striving, found a way to adjust it to his telescope, and pointed the telescope at a star. The stars are but distant suns, he reasoned. If they give light enough, they too must yield up their secrets.

Eagerly, with bated breath, William Huggins in his private London Observatory, pointed the telescope, and for a time—as he himself has told it—scarcely dared to look for the answer.

But when he did look, the answer was affirmative. His 8-inch telescope—an object glass made by Alvan Clark, the famous American optician—gathered light enough to produce a spectrum.

Fig. 69.—Robert Wilhelm Bunsen (1811-1899). (Adapted from half-tone in Williams' *Story of Nineteenth Century Science*.)

The star, like the sun, could be brought to earth for the analysis of its substance.

Huggins himself tells us that, when he first heard of Kirchhoff's great discovery, a feeling as of inspiration seized him. "I felt as if I had it now in my power to lift a veil that had never before been lifted; as if a key had been put into my hands which would unlock a door which had been regarded as forever

closed to man—the veil and door behind which lay the unknown mystery of the true nature of the heavenly bodies."

Huggins Analyzes the Stars

And now he had the proof that his optimistic dreamings had not been in vain.

In that hour, the new stellar astronomy was born. The entire complexion of astronomical research was changed. The brightest star, in the field of the most powerful telescope, remains only a point of light. But in the eye of the spectroscope, that point of light is transformed into a material structure, of discoverable substance.

The magic wand of the new astronomy brings the stars to earth.

Among the outstanding revelations of the spectroscope in the hands of Dr. Huggins (Sir William Huggins as he came to be) were the records of comets and of nebulae.

Comets were found to have so-called "fluted bands" in their spectra, which were interpreted as showing the presence of carbon.

To make doubly sure, the comet's spectrum was compared with the spectrum of a current olefiant gas, ignited by a spark. The gas was confined in a small holder attached to the end of the telescope, so that its spectrum, when a spark was taken in it could be seen side by side with that of the comet. The two spectrums agreed in all respects. "Thus," says the investigator, "the comet, though 'subtle as a sphinx,' had at last yielded up its secret. The principal part of its light was emitted by luminous vapor of carbon."

It is added that this was altogether in harmony with the observation of the nature of the gas found occluded in meteorites.

As to the investigation of the spectra of nebulae, the revela-

tions were so surprising that Dr. Huggins long afterwards spoke almost with awe of the feelings aroused in his mind in the day of discovery, back in 1864.

"To this day," he said long afterwards, "these observations remained associated in my memory with the profound awe which I felt on looking for the first time at that which no eye of man had seen, and which even the scientific imagination could not foreshow."

The Strange Light of Nebulae

He goes on to say that the attempt to test the spectrum of a nebula seemed hopeless, because of the faintness of the luminosity. Yet he determined to make the effort.

Again in describing his success he reverts to "the feeling of excited suspense, mingled with a degree of awe, with which, after a few moments of hesitation, I put my eye to the spectroscope. Was I not about to look into a secret place of creation?"

And when he looked, awe gave way to astonishment.

For he found no spectrum such as he expected, but a single bright line only. The light of the nebula was monochromatic, and so, unlike any other light he had subjected to prismatic examination, could not be extended to form a complete spectrum. A little closer looking showed two other bright lines on the side toward the blue, all three lines being separated by intervals relatively dark.

"The riddle of the nebulae was solved. The answer which had come to us in the light itself, read: not an aggregation of stars, but a luminous gas."

The explanation of this surprise is that nebulae were then believed to represent merely aggregations of stars at an enormous distance.

The great six-foot reflecting telescope of Lord Rosse—the

largest telescope hitherto constructed—had resolved nebulae into stars, just as Galileo's first lens had resolved the Milky Way, or as Herschel had resolved nebulae that resisted all instruments but his own.

And so it was assumed, and considered a fair inference, that with sufficient power, perhaps some day to be attained, all

Fig. 70.—Lord Rosse (1800-1867). (Adapted from Hutchinson's *Splendour of the Heavens*. Source not stated.)

nebulae would yield; hence that all are in reality what Herschel had at first thought them—vastly distant "island universes," composed of aggregations of stars, comparable to our own galactic system.

Now the spectrum in Dr. Huggins' hands showed that this cannot be true, at least of some nebulae.

The one that he was examining was no system of stars, but

Plate XVI: Joseph Fraunhofer (1787-1826)
(Pencil interpretation of an engraving of untraced origin)

a mass of glowing gases. The most conspicuous bright line could not be ascribed to any known terrestrial element; nor, indeed, to any element discovered in sun or stars.

It was presently christened "Nebulium."

Parenthetically it may be added that the nature of this gas remained a secret for more than sixty years. It was not until 1927 that Dr. I. S. Bowen, of Pasadena, California, proved, to the astonishment of astronomers and physicists alike, that "nebulium" is merely the chief constituents of the air we breathe, namely: oxygen and nitrogen, the atoms of which, in the extremely rarified nebulae gas, are in a singly and doubly ionised condition—that is to say partially disrupted by loss of one or two orbital electrons. Hence the modified character of the spectrum line which masked instead of revealing the true nature of the prominent constituents of the nebulae.

It was found presently that some other nebulae give a continuous spectrum, suggestive of incandescent solids or liquids; proving that these curious celestial objects are of different types.

It has become customary, indeed, to speak of four classes of nebulae. As to three of them, there is no full consensus of opinion among astronomers. But the fourth, known as spiral nebulae, of which we shall hear a good deal more before we are through, are believed to be by no means merely gaseous clouds, but vast systems of stellar bodies lying beyond the confines of our galactic system.

The story of the spectroscope is not finished. It is only begun. But before we follow farther the revelations of this strange Aladdin's lamp of the new astronomy, we must learn something of another equally novel and no less wizard-like instrument that came to the aid of the astronomer almost at the same time, and

in cooperation with the other transformed the essential character of the task of the star-gazer.

I mean, of course, the photographic camera.

XXIV

BONDS—DRAPERS—PICKERING—STAR PORTRAITURE

THE new work of testing the chemistry of stars with the spectroscope had not proceeded far, before it occurred to various of the workers that the photographic negatives might conceivably be used to keep a permanent record of their observations.

This was the period when the new art of photography—the incredible art, by which portraits of unbelievable accuracy and detail were painted by sunlight itself on a chemically treated sheet of glass or metal—had taken the world by storm.

Just twenty years before the secret of the Fraunhofer lines in the spectrum was solved by Kirchhoff, the famous French physicist and astronomer, Arago, had communicated to the Academy of Science details of the perfection of a method of making sun-pictures devised by another Frenchman, Louis Daguerre.

It was well known that Daguerre had for many years been working on the problem. At last he had succeeded.

At once the news spread to all quarters of the globe, and "da-

guerreotype" portraits were accounted the greatest wonder of a wonderful generation.

The imaginative Arago conceived the idea that the new process might be applied to the portraiture of the heavenly bodies.

The same idea occurred to one of the most virile and imaginative men in America, Dr. John William Draper, a young

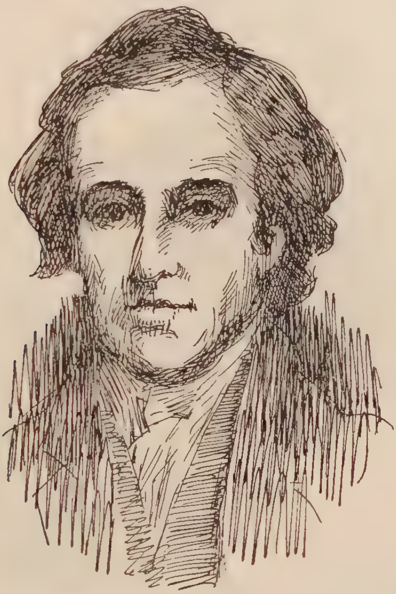

FIG. 71.—Dominique Francois Arago (1786-1853). (Adapted from tone in Williams' *Story of Nineteenth Century Science.*)

physician who had recently been appointed to the position of Professor of Chemistry in New York University.

And Draper almost immediately put the idea into execution.

In 1840, having already tried his hand at human portraiture, he attached a sensitized sheet of metal at the focus of a telescope, and took a portrait of the moon. A wonderful portrait it was—

not indeed, according to the standards of a later day, when the art of photography had made the daguerreotype method obsolete.

But considered in its time, at the very beginnings of a new art, the taking of that portrait of the moon was an amazing achievement.

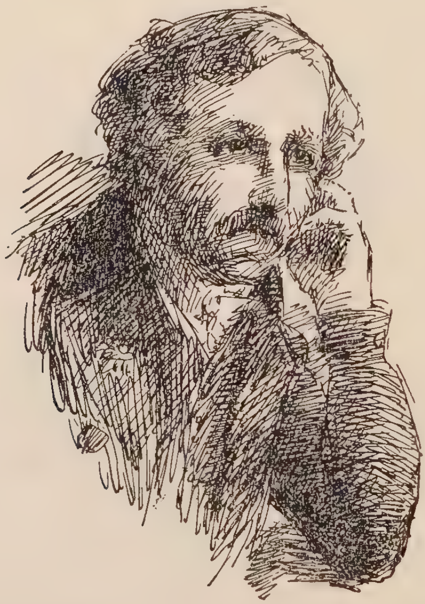

FIG. 72.—L. J. M. Daguerre (1789-1851). (Adapted from Williams' *Story of Nineteenth Century Science*.)

The New Art of Celestial Photography

With that accomplishment of Dr. William Draper, the English-born American, the new art and science of celestial photography was born.

A new method had been introduced which, when perfected, was to revolutionize the traditional methods of observation of astronomy, transforming the telescope into a camera, and the

afore-time star-gazing astronomer into a scrutinizer of negatives in the laboratory.

But naturally such a transformation was not effected in a day. The moon had indeed sat for her portrait in 1840. But ten years elapsed before the new method was applied to the portraiture of the stars.

FIG. 73.—John W. Draper (1811-1882). (Adapted from Williams' *Story of Nineteenth Century Science.* Source not traced.)

Then at Harvard Observatory, where Bond followed Bond as director, an American named Whipple, under the direction of the celebrated William Cranch Bond (known as the elder Bond) took a daguerreotype of the image of the bright stars Alpha Lyrae and Castor.

The younger Bond (George Phillips), recording this achievement a few years later, speaks of it as an interesting demon-

stration of the possibility of such an achievement but goes on to say that Mr. Whipple subsequently gave his attention to making photographs of the moon and sun, "and the stars were left to themselves."

Nevertheless celestial photography had been born, just at the middle of the 19th century. Two of the brighter stars, in sequence, had sat for their portrait. Moreover, the first of star-photographers was soon to return to this field, and in cooperation with a confrère named Black, to test the newly developed collodion process in the field of star-photography.

This was in March, 1857.

Writing in that year, George Bond, who evidently was directly associated in the enterprise, reports that:

"The disconnected attempts we have thus far been enabled to make are of the highest interest, and suggest possibilities in the future which one can scarcely trust himself to speculate upon."

And he adds prophetically, "could another step in advance be taken equal to that gained since 1850, the consequence could not fail of being of incalculable importance in astronomy."

Just what the progress of seven years had been, Bond reveals in these words:

"The same object, Alpha Lyrae, which in 1850 required 100 seconds to impart its image to the plate, and even then imperfectly, is now photographed instantaneously with a symmetrical disk, perfectly fit for exact micrometer measures. We then were confined to a dozen or two of the brightest stars, whereas now we take all that are visible to the naked eye. Even from week to week we can distinguish decided progress."

The young enthusiast speaks further of the beauty and con-

venience of the method, scarcely to be appreciated without actually witnessing it for oneself; tells that stars of the sixth magnitude are the smallest that as yet can be recorded; but expresses confidence that still greater advances will be made in the near future. In particular, he notes that the relative magnitudes of the stars are recorded on the photographic plates by the intensity and size of the images; and that the measurements of distances and angles of position of the double stars, as ascertained by many trials on our earliest impressions, "are as exact as the best micrometric work."

Here, then, is not only a good beginning in celestial photography, but a clear forecast of the great future of the new art and science.

George Bond himself became director of the Harvard Observatory on the death of his father two years later (in 1859). But his own untimely death occurred in 1865, before the next great advance in photography had been perfected—the dry-plate process—which was presently to make the realities of celestial photography transcend immeasurably the most optimistic forecast.

Many Workers in the New Field

But by this time other workers were in the field. Indeed, there were European investigators who had almost from the outset paralleled the work of the American pioneers.

As early as 1845, two famous Frenchmen, Foucault and Fizeau, on advice of Arago, had undertaken to make solar daguerreotypes. And during the years from 1853 to 1857, de la Rue made experiments which culminated in his development of a photoheliograph, or sun-camera, for the Kew Observatory.

Thenceforth solar photographs would be taken daily at Kew and at the Royal Observatory at Greenwich.

Meantime the first photographs of a solar eclipse had been taken by Busch, at Königsberg, in 1851, and by Bartlet at West Point in 1854. In 1860 eclipse photographs of high scientific importance were taken by the Italian astronomer Father Secchi and by Warren de la Rue.

FIG. 74.—Jean Bernard Lèon Foucault (1819-1868). (Adapted from half-tone in Bell's *The Telescope*. Source not stated.)

In America, Lewis Rutherfurd in 1864 made an eleven-and-a-half-inch objective, which was corrected only for the photographic rays, and by means of this obtained the finest photograph of the moon which had yet been made. Dr. E. S. Holden who makes this appraisal, records also that Dr. Henry Draper, son of the pioneer in the field, about the same time made a fifteen-inch reflecting telescope though he also took excellent lunar photographs.

These lunar photographs of the younger Draper, indeed, were so sharply outlined that, from the original picture of about two-and-a-half inches, they could be enlarged to a diameter of three or four feet.

And now it was time for the attempted union of the new photographic method with the even newer spectroscopic method that the New Astronomy might come to full maturity.

The Union of Camera and Spectroscope

As camera and spectroscope were both developments of the physical laboratory, it was inevitable that most workers who were interested in one were also interested in the other.

The possibility that the negative might be induced to record the findings of the spectroscope did not escape Huggins and Miller in their London laboratory-observatory and they early attempted to combine the two. Photography was not then sufficiently advanced, however, to make the attempt notably successful. It was not until the dry plate came that celestial photography could take its place as a secure, convenient, and universally available method.

Marvelous star-charts had by this time been taken with the old wet plate apparatus. Even stars of the ninth magnitude were included in the plates made with Dr. Rutherfurd's eleven-inch telescope.

But even these results were quickly to be surpassed when the silver-bromine plate was available.

Huggins had, indeed, obtained as early as 1863 a photographic image of the spectrum of Sirius, but this was of little value because it contained no lines.

The first successful photograph of the spectrum of a star, in which the essential lines showed, was made by Dr. Henry Draper in 1872.

Huggins took up the work actively again in 1875, in connection with his unremitted spectrum work, and the following year a photograph of the spectrum of Alpha Lyrae was shown by him at the Royal Society. In the same year Draper secured valuable spectrum photographs of various of the brightest stars.

In 1882, both Draper and Huggins obtained photographs of the spectrum of the nebula in Orion.

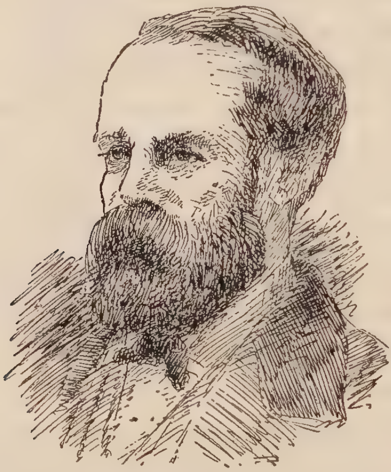

FIG. 75.—Henry Draper (1837-1882). (Adapted from an engraving of untraced origin.)

This achievement—recording the spectrum of the faintest of celestial objects—marked the full maturity of the photographic method. Henceforth spectroscopic photography was to take and hold a major position in the astronomic world.

Of course the camera would continue to be used by itself in making star-charts. Indeed, a colossal work in this field awaited it: nothing less than the star-charting of the entire firmament.

But the stupendously significant achievement of the New As-

tronomy in the ensuing half century was to be the result of the coalition of the telescope, spectroscope and photographic negative indissolubly united.

The old instrument and two new ones were to constitute a triumvirate of incomparable power in an altogether new type of exploration of the secret places of the universe.

Photometry Developed at Harvard

Wherever in the world telescopes were available, one aspect or another of the new investigation of the heavens would be ardently prosecuted.

But, as was fitting, Harvard University, scene of the pioneer efforts at celestial photography, was well in the van. In particular, the early researches there (1882 and subsequently) were directed toward the establishment of a standard of relative brightness of stars, raising "photometry" to the plane of a highly developed science.

When it was decided to establish a memorial to Dr. Henry Draper (who died only a few months later than his father, in 1882), it was arranged to have this associated with Harvard Observatory, and the great star catalogue, with its hundreds of thousands of photographic records of star-spectra, was in due course issued.

It was dedicated to Dr. Henry Draper, and its now famous classification is generally referred to as the Draper Classification.

We shall have occasion to examine this new interpretation of the nature of the stars more in detail in another connection. For the moment we are concerned with the general character of the investigation of stellar life made possible by the use of spectroscope and photographic plate, separately or in unison, rather than with detailed results.

The Chemistry of the Stars

We have already seen that the first new field to be entered was the domain of star-chemistry; that is to say, the investigation of the chemical composition of the celestial bodies.

We saw that certain familiar terrestrial substances were at once revealed as constituents of the sun and of the brighter stars.

It remains to be said that before the close of the nineteenth century, about half of the elements known on the earth had been detected in the sun. One new element had been discovered in the sun, and hence given the name helium, or sun-element. Subsequently this element was found to be a hitherto unsuspected constituent of the earth's atmosphere (in minute quantities) and a more abundant constituent of the gases in certain oil wells, besides being generally distributed through the mineral strata of the earth.

The element thus discovered by the Englishman, Sir Norman Lockyer, of whom we shall hear more presently, was to be known later as a by-product of the decomposition of radioactive elements and to gain popular fame as the gas, which, because of its non-inflammable character, is a desirable substitute for hydrogen in filling balloons.

From the present standpoint, the significance of the discovery of this element is that it called attention to the capacity of the spectroscope in the domain of solar chemistry.

That a terrestrial element in universal distribution should have been altogether overlooked by laboratory analysts generation after generation, to be discovered here only after an astronomer had located it in the sun and taught the chemist how to search for it in his laboratory, was a sequence of events that appealed to the popular imagination.

Probably this episode did more than any other single achievement to give people in general an inkling of the weird capacity of the New Astronomy to fathom secrets of the far-off heavenly bodies.

But the spectroscope has a second elemental capacity if possible even more astounding.

The Spectroscope Measures Star-Speeds

It can reach out into space, almost to the confines of telescopic vision, and measure the exact speed of flight of stars that are moving toward us or away from us in the line of sight. By the same capacity, it can prove that a binary system is revolving and how fast, by noticing the approach or recession of its components.

Strangest of all, it can reveal the existence of invisible stars—"dark stars," the very phrase a paradox!—as the companions of visible ones, the shifting spectre of the latter revealing an orbital movement.

Presently thousands of such "spectroscopic binaries" were revealed, doubles that lie far beyond the most searching powers of the unaided telescope. Just as the line-of-sight speed of hundreds of thousands of stars is revealed, whose movements could by no other method available conceivably be tested.

And of course the photographic negative makes permanent record of these things.

Incidentally it may be added that a single negative may enscroll records the interpretations of which will involve hours, days, or even weeks of meticulous scrutiny and measurement on the part of a keen-eyed laboratory worker.

A word now as to the manner in which the spectroscope records its weirdly penetrative observations of the speed of stars that may be distant a hundred or a thousand light-years.

Fantastic as the results seem, the principle involved is simplicity itself.

It has to do simply with a shift of position of Fraunhofer lines in the spectrum. As long ago as 1841, Doppler surmised that if the incandescent object that produces the spectrum is moving toward the observer, the lines of the spectrum should crowd a little toward the violet end; whereas, under the opposite condition, they should move toward the red end of the spectrum.

The principle involved is no different from the crowding together of sound waves which results when a whistling locomotive, for example, rushes toward the listener, causing the sound to rise in pitch; while, after the engine passes, the sound correspondingly drops as the sound waves are, in effect, pulled wider apart by the receding whistle.

The test as to whether such a shift occurs in the case of moving stellar bodies, could be made only when the real meaning of the Fraunhofer lines had been detected; for of course the position of a line in the scale depends entirely on the character of the incandescent body, or the reversing gas, that causes it.

But when it is known that a certain line, or group of lines, represents, let us say, hydrogen, it becomes necessary only to compare the hydrogen spectrum of a star with a hydrogen spectrum produced in the laboratory. When these two spectra are put side by side, or superimposed, if it is seen that the characteristic lines are shifted in one direction or another from their normal position, measurement or the exact amount of this shift may be interpreted in terms of actual speed, toward us or away from us, of the stellar body.

That is the whole secret. But the results of application of the principle have been astonishing.

The stars are so distant that only a few of the nearest ones can be tested for parallax by the trigonometric method which we saw illustrated in Bessel's feat of measuring the distance of 61 Cygni.

The relative distances of a larger number of stars may be inferred in general terms from the amount of their so-called proper motion—their backward drift due really to the forward flight of the solar system from which our observations are made.

This could tell something, did indeed tell much, as to the movements of a large number of relatively neighborly stars.

But not the faintest conception could be gained as to the probable movements of the steller hosts in general, and in particular the more distant ones, until spectroscopic photography made records of star movements by thousands available for measurement.

Weighing Invisible Stars

Moreover, one revelation linking with another, it was possible in numberless cases to estimate the bulk of a binary system, one member of which might be totally invisible, through spectroscopic observation of the rate of mutual revolution.

And, to complete the necromantic appraisal, the actual distances of a multitude of stars were revealed through "spectroscopic parallax"—utilizing new knowledge as to the mutual relations of mass and brilliancy, in connection with the equally new knowledge of the constitution of the different types of stellar bodies.

Thus, whereas more than two centuries of telescopic observation had elapsed before the distance of a single star was measured, and at best only a few stars had proved measurable, by the direct-observation method; the distances of thousands of

stars were now revealed at a single coup by the joint endeavor of spectroscope and photographic negative.

These new aids served not merely to sharpen the observing eye, as the telescope had done, but to supplant the eye altogether for purposes of direct observation by proving their fitness for functionings of a type for which the unaided eye is totally unfitted.

Direct observation of images seen through the lens of the greatest refractor or in the focus of the largest reflector, reveal the stars only as points of light of varying brilliancy and only slightly varied color, and give no information whatsoever (except by vague inference) as to the chemical constitution, actual distance, real size, or line-of-sight movement of the myriad hosts of the firmament. Spectroscopic photographs, on the other hand, give definite information as to all these mysterious things.

Many modern telescopes are made to focus the actinic rays toward the violet end of the spectrum rather than the yellow rays that the eye sees best. Such telescopes are of course fitted with spectroscopes and negatives rather than with visual eyepieces.

They are, in a word, cameras for star portraiture. The astronomers who use them have largely ceased to be star-gazers. Some of them are not even spoken of as astronomers, but as astrophysicists.

The advance of telescopic vision upon naked-eye observation was not greater than the modern advance from direct telescopic observation to telescope-spectroscopy and photography.

The Harvard Library of Star Portraits

The negative exposed for a long period in the focus of a great telescope shows myriads of dots, each representing a star, that the eye, even using a telescope of equal power, does not register.

Plate XVII: WILLIAM HUGGINS (1824-1910)
(Pencil sketch based on half-tone in Abbot's *The Earth and the Stars* said to be from a portrait at the Royal Society of England)

Thus literally billions of stars are recorded of the 22nd and 23rd magnitudes, the existence of which could otherwise only be surmised—since the eye (with present telescopic aid) sees none beyond the 21st magnitude.

And of course the spectrographic portraits of millions of stars of larger magnitudes furnish permanent records of tell-tale lines which could by no chance be interpreted except as they are registered on the unchanging photographic plate.

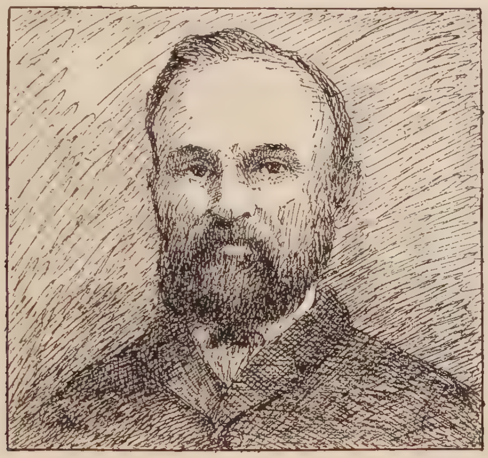

FIG. 76.—E. C. Pickering (1846-1919). (Crow-quilled from a photograph of an untraced half-tone.)

The work of creating what Dr. Abbot has spoken of as a "photographic library of the sky, wherein is daily recorded the brightness, spectrum, and places of thousands of stars," has been preeminently the task of the Harvard University Observatory, under auspices of the Henry Draper Memorial, and this constitutes the important life work of the fourth director of the observatory, Professor E. C. Pickering (1846-1919).

He inaugurated extensive investigations in photographic pho-

tometry, variable stars, and spectroscopy, and devised many of the instruments necessary for these researches. I quote here Prof. Pickering's successor, Professor Harlow Shapley, who further states that Pickering measured personally the majority of the magnitudes in the Harvard Photometries.

An important incidental use of the Harvard "Library" of star portraits is that if at any time a new celestial object is discovered, the Harvard plates will furnish its previous history for many years. If an observer sees what he thinks is a new star, an unlisted comet, or a planetoid, he can check his observation by reference to plates in the Harvard collection, which will show unequivocally whether a stellar body previously existed at the location in question.

Prof. Pickering has recorded that his first experiments were made in May, 1885, by placing a prism of 30-degree angle in front of the object-glass of the lens. Here he was following out a method devised by Father Secchi, the Italian pioneer in this field.

Pickering's Early Methods and Results

In taking the photographs, no clock work was used. In photographing stars without the spectroscope, it is necessary to have the telescope move continuously, at precisely the rate to counteract the earth's movement, so that the image of the star shall be sharp, and not a streak on the plate. But in photographing the spectrum of a star, it is desirable that the image should shift, in order that the spectrum shall be spread out into a band, instead of being a mere line as it otherwise would be.

In the thin strip of light that would represent the spectrum as an individual star, the Fraunhofer "lines" would be only points, not clearly discernible. It is only when the image shifts on

the plate that the spectrum becomes a band, across which the points have recorded themselves as lines.

That is why a photograph of spectroscopic star-portraits looks like a collection of tiny fragments of ribbon, crossed by lines. It is obvious at once that such portraits can be compared one with another, as well as studied individually. It is equally obvious that direct-eye observation of the spectrum would furnish no material for such study or comparison.

Fig. 77.—Spectra of Stars. (Adapted from an untraced photograph.)

Subsequently prisms were constructed having angles of about five and fifteen degrees, and clear apertures of twenty centimetres. These could be placed over the object-glass of the photographic telescope without reducing the aperture. The one of larger angle was found more satisfactory for most purposes.

It was found desirable presently to make exposures longer than the two or three minutes that had proved sufficient for bright stars. A method was developed of using the clock-work apparatus to drive the telescope, but varying the rate of the clock a little, in order to give any width of spectrum desired.

It was found that a width of about one millemetre was needed to show the fainter line. This distance would be traversed by an equatorial star in about twelve seconds. The longest time that it is ordinarily convenient to expose a plate is about an hour.

"If then," says Prof. Pickering, "the clock is made to gain or lose twelve seconds an hour, it will have the rate best suited for the spectra of the faintest stars. A mean-time clock loses about ten seconds an hour. It is only necessary to substitute a mean-time clock for the sidereal clock to produce the required rate."

A "mean-time" clock is of course a clock that keeps standard time. Naturally the astronomer must ordinarily use sidereal time, else his machinery will not follow the stars accurately.

After 1886, when the widow of Henry Draper established the memorial to her husband, the project was carried forward of photographing the entire sky. Even before the establishment of the auxiliary observatory at Arequipa in South America, the cataloguing had begun of the spectra of all stars north of the tropic of Capricorn of the sixth magnitude and brighter, together with more extensive catalogues of spectra of stars brighter than the eighth magnitude, and a detailed study of the spectra of the bright stars.

It was this project, as ultimately carried forward by Prof. Pickering and his associate, that resulted in the production of the "library" already referred to, and gave such insight into the nature of the stars as to lead to a more detailed classification of all the stars into typical groups than had hitherto been possible—the only earlier work of consequence along the same lines being that of Father Secchi in Italy.

The First Spectroscopic Binary

This classification, which became famous as the Harvard or Draper Memorial Classification will be referred to more at length

in a later chapter. With slight modifications it remains the standard classification of the stars, through which all are brought into a few groups, with numerous subdivisions, the basis for grouping being the chemical composition of the various types, as registered by the tell-tale Fraunhofer lines of the photographic spectrum.

Long before this work was completed, however, very notable discoveries had attended the study of the star-portraits now for the first time provided in vast numbers.

One of the most notable pieces of work done in connection with the new spectrum photographs was a careful study by Miss A. C. Maury, a niece of Dr. Henry Draper. She compared with meticulous care a series of spectrum-portraits, taken on seventy nights, of the star known as Zeta Ursae Majoris (the middle star in the handle of the Big Dipper, better known as Mizar), for particular observation of what is known as the K line. This line is ordinarily a conspicuous single one, but Miss Maury had discovered that on certain of the pictures it had been transformed into a fainter double line. Further observation showed that there was an alternation between single and double lines, with an intermediate somewhat hazy stage. The line appeared to be double at intervals of fifty-two days.

It was found, too, that the hydrogen line in the various spectrums seemed to be widened when the K line was doubled, and that other lines less sharply defined were also doubled simultaneously.

Summarizing the results of the observations, in an article in the *American Journal of Science* for 1890, Professor Pickering said:

"The only satisfactory explanation of this phenomenon as yet proposed is that the brighter component of this star is itself a double star having components nearly equal in brightness and too close to have been separated as yet visually. Also that the time of revolution of the system is 104 days. When one component is approaching the earth all the lines in its spectrum will be moved toward the blue end, while all the lines in the spectrum of the other component will be moved by an equal amount in the opposite direction if their masses are equal. Each line will thus be separated into two. When the motion becomes perpendicular to the line of sight the spectral lines recover their true wave length and become single."

It was further stated that an idea of the actual dimensions of the system might be derived from the detailed measurements of the shift of spectral lines. It was estimated that the distance traveled by one component of the star regarding the other would be 900 million miles, and the distance apart of the two components 143 million miles, or about that of Mars and the sun. The combined mass would be about forty times that of the sun, in order to give the required period.

These are extraordinary revelations to be made by the little fragments of ribbons that represent star portraits. In future, the pursuit of spectroscopic binaries was to become one of the most fruitful occupations of devotees of the new science of astrophysics.

Forty years later (1924) Lick Observatory, where Aitken and Hussey had specialized in double stars, issued a catalogue of spectroscopic binaries listing more than a thousand stars of this type.

XXV

NORMAN LOCKYER—STARS IN THE MAKING

THE universe into which now, with the aid of spectroscope and camera, the investigators penetrated, began to assume proportions that staggered even the astronomical imagination. A generation before, the distances to the "parallactic stars," which are our nearest neighbors had seemed stupendous.

Light travels at the speed of 186,000 miles per second. At that rate, it compasses a vast distance in an hour, an inconceivable distance in a year.

Yet the nearest star has been found to be four and a third light-years distant; the next nearest ones twice and thrice that. It will be recalled that Bessel had estimated the distance of 61 Cygni, in accordance with his measurement, as 600,000 times the distance of the sun.

Stated in words, that becomes more than fifty-five trillion miles; in figures, 55,000,000,000,000.

Whether stated in words or depicted in figures, such distances are totally inconceivable. Terrestrial experience enables us to form clear pictures of hundreds of miles, even of thousands; but millions lie altogether beyond our "frame of reference."

Yet at least a vague conception of relative differences may be appreciable. So when it is stated that, whereas the very nearest stars are grouped within a radius of from four and a half to ten light-years, the great bulk of the stars, even the naked-eye visibles, lie at distances of 50, 100, or 1000 light-years, the terms are not quite without meaning.

Sounding the Universe

And when we go on from this to multiples of even these larger figures—speaking of stars at the distance of 50,000 light-years, or 100,000, 500,000, or even 1,000,000 light-years—we at least gain an impression of a stellar system of not merely inconceivable but overwhelming stupendousness, to describe which no words have the remotest semblance of adequacy.

Tangible illustrations may serve at least to stimulate the imagination.

Sir James Jeans suggests that the stars are perhaps as numerous in the galaxy as particles of dust scattered across the great city of London. Our sun, of course, would be one of the particles of dust—of about average size. Possibly it may help to reflect that, according to calculations, if our sun were viewed from the nearest star, it would shine as a rather faint star of second magnitude. Our earth, of course, would be totally invisible, and even the giant Jupiter would become a star of about the 23rd magnitude, beyond the limit of vision of the most powerful terrestrial telescope, but conceivably registered on the photographic plate as a mere particle of light removed by only a fraction of a second of arc from the sun itself.

If now we were to chart a celestial map according to scale, in which the distance between our sun and the nearest star (an actual distance of four and a third light-years) is represented by one inch, the flecks of dust representing the remaining stars of the nearest groups would be at distances of from a foot to a yard; the scattered flecks of dust representing stars of average distance would be found here and there in every direction at distances of a few yards to several miles; while the dust flecks representing the most distant portions of the Milky Way might be distant a thousand miles, and the little drifts of dust that

pose as spiral nebulae may be at some such distance, perhaps, as that which separates New York from Tokio.

Such crude illustrations, I repeat, may stimulate the imagination, but at best may by no means make the dimensions of the sidereal universe in any proper sense conceivable.

But in proportion as these figures lie beyond the grasp of imagination, they have better served to bring home to us the spectacular character of the achievement of the little prism of glass (or finely ruled metal plate) that constitutes the heart of the spectroscope, and of the gelatin-coated glass plate of the photographic apparatus.

Penetrating the Atom

And even yet the most spectacular and astounding achievement of these accessories of the new astronomy has not been told.

Now we are to note that, in the very act of revealing the secrets of the universe that have just been outlined, the spectroscope has revealed also, and the photographic plate recorded, secrets of atomic structure and constitution which are no less wonderful in their way—and to contemporary science even more bewildering—than the revelation of those secrets of the macroscopic world.

Our conception today of the nature of matter itself has been even more fundamentally transformed than our conception of the structure of the universe.

And this transformation, like the other, found its origin in spectroscopic study of the sun and stars.

The evidence that led to the revolutionary conception of the nature of matter was at first altogether puzzling to astronomers. When its probable import began to be realized, only a few astronomers, and perhaps no physicists at all, were in the least pre-

pared to give it credence. And little wonder. For the evidence suggested that the atom itself—then held to be the fundamental structure of all matter—might be disrupted in the crucible of the sun; an atom of oxygen or calcium or iron, for example, transformed into something that is not oxygen or calcium or iron.

Such a suggestion was utterly heretical from the standpoint of traditional science.

Few doctrines seemed better established than the doctrine that matter is indestructible and that its elementary atoms are non-transmutable.

Were we to suppose that this law is abrogated in the sun and stars, when we have just learned that these bodies are constituted of familiar terrestrial elements?

The majority of observers and experimenters of the latter part of the 19th century were by no means prepared to accept so nihilistic a thesis.

If the spectra of sun or stars or nebulae showed groupings of Fraunhofer lines that did not correspond to any terrestrial elements, it was surely simpler to assume that these represented undiscovered elements, perhaps only stellar, perhaps also terrestrial, than to assume that elements hitherto known had been dissociated or decompounded even under the conditions of excessive heat and pressure that exist in the vast sidereal bodies.

The Imaginative Lockyer

A few exceptional men, however, took the opposite view. Notable among these was Sir Norman Lockyer, discoverer jointly with P. J. C. Janssen of helium, one of the keenest-eyed users of the spectroscope, and perhaps the most creatively imaginative astronomer of his generation.

The smoky atmosphere of South Kensington, London, did not

prevent Lockyer from prosecuting actively and with marked success the methods of the new astronomy.

His place of observation was known, indeed, as the Solar Physics Observatory.

The term Astrophysics was coming into vogue, as an appropriate name for the new type of astronomical investigation, which

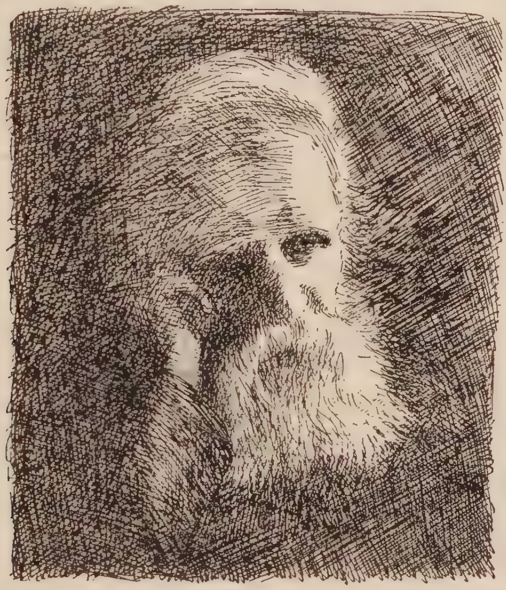

FIG. 78.—P. J. C. Janssen (1824-1907). (Crow-quilled from half-tone in Shapley and Howarth's *Source Book in Astronomy*. Origin not traced.)

concerned itself, as we have seen, with the constitution of stellar bodies and the construction of the universe rather than with mere observation and measurement of the location of stars.

The institution of which Lockyer was the head, was one of the first, if not the very first, whose name suggested the character of the new astronomy.

Obviously the phrase "Solar Physics" would have had only the vaguest meaning in the day of the old astronomy, prior to 1859.

A recent commentator has said very justly of Lockyer that it was typical of the quality of his mind that he could never be satisfied with discovering a fact without trying immediately to understand the reason for it. "When a second fact was discovered, it had to be brought into relation with the first, and if this could not be done consistently with current ideas, current ideas had to be abandoned."

Add that Lockyer was no less ready to abandon a "current idea" because it chanced to be an idea that he had himself originated, and we have a true picture of the mental attitude of a man born to be an innovator in his field of science, yet bound to submit every new hypothesis to experimental tests, and to weigh evidences impartially, without regard to its novelty.

Such, be it understood, is by no means the mental attitude of scientific investigators in general. The average man of science is in this regard not far different from the average layman. Perhaps unconsciously, but none the less consistently, he is impelled, when confronted with new discoveries that he cannot at once bring into relation with current ideas, to abandon, not the current ideas, but the new discoveries.

That is why it takes two or three generations for a really revolutionary idea, however well fortified, to make its way in the scientific world.

Witness, if you wish a striking example, Tycho Brahe, the great observer, confronted by the Copernican conception.

Witness by way of contrast, Kepler and Galileo, men of imaginative genius—observers, but also thinkers.

Of the type of Galileo and Kepler and perhaps not below the exalted plane of their creative mentalities, was Sir Norman Lockyer.

Like Kepler, Galileo, and Newton, and perhaps in greater measure than any one astronomer subsequent to them, he was the originator of new ideas and theories, based on experimental evidence in large measure of his own finding, and tested in a forge fanned by enthusiasm held sanely in check by logical reasoning.

The Dissociation of Elements

The new physical conception with which Lockyer's name will always be associated, was the conception of the dissociation of elements in the furnace of the sun. The expansive cosmogonic speculation that grew out of this thesis was called by its author the Meteoritic Hypothesis.

It constitutes the most comprehensive scheme of the origin and evolution of the stars that hitherto had been propounded.

We cannot better summarize the status of the new astronomy, as represented by the advance guard of its proponent, than by briefly presenting the essentials of the hypothesis of the dissociation of chemical elements and the story of the history of the universe as conceived by the meteoritic hypothesis.

The present presentation may be brief, because we shall return to the subject in a later chapter.

The gist of Lockyer's dissociation hypothesis was merely that elementary atoms, hitherto supposed to be elastic, indivisible particles, are variously modified or dissociated in the crucible of the sun.

We shall see in later chapters that this conception became a commonplace of physical science only a generation after the

time when its author vainly strove to convince his contemporaries of its validity.

Writing recently, Prof. Herbert Dingle, of the Royal College of Science, London, makes this unequivocal declaration:

"Taking a comprehensive view of the theory, we can see that, though Lockyer's conceptions were incomplete, they were always essentially right. Though the character of the dissociation which he conceived has not been established—though it has turned out to be a physical rather than a chemical process—yet dissociation of a special kind is now acknowledged to take place. Lockyer's spectroscopic discoveries and theories will, in all probability, prove to be his most lasting memorial in the realm of pure science."

The Meteoritic Hypothesis

The meteoritic hypothesis views the universe constructively, and attempts to explain the origin and destiny of the stellar bodies.

Outlined in few words, it is an attempt to explain all the major phenomena of the universe as due directly or indirectly to the gravitational impact of such meteoric particles, or specks of cosmic dust, as comets are composed of.

Nebulae are regarded as vast cometary clouds, with particles more or less widely separated, giving out gases through meteoric collisions, internal or external, and perhaps glowing also with electric or phosphorescent light.

Gravity eventually brings the nebular particles into closer aggregations, and increased collisions finally vaporize the entire mass, forming planetary nebulae and gaseous stars.

Continued condensation may make the stellar mass hotter and more luminous for a time, but eventually leads to its liquefaction,

and ultimate consolidation—the aforetime nebulae becoming in the end a dark or planetary star.

The exact correlation which Lockyer attempted to point out between successive stages of meteoric condensation and the various types of observed stellar bodies did not meet with unanimous acceptance. Mr. Ranuard, for example, suggested that the visible nebulae may not be nascent stars, but emanations from stars, and that the true pre-stellar nebulae are invisible until condensed to stellar proportions. But such details aside, the broad general hypothesis that all the bodies of the universe are, so to speak, of a single species—that nebulae (including comets), stars of all types, and planets, are but varying stages in the life-history of a single race or type of cosmic organisms—was accepted by the contemporaries of Lockyer as having the highest warrant of scientific probability.

All this, clearly, is but an amplification of that nebular hypothesis which, long before the spectroscope gave us warrant accurately to judge our sidereal neighbors, had boldly imagined the development of stars out of nebulae and of planets out of stars.

World-Smashing

But Lockyer's hypothesis does not stop with this. Having traced the developmental process from the nebular to the dark star, it sees no cause to abandon this dark star to its fate by assuming, as the original speculation assumed, that this is a culminating and final stage of cosmic existence.

For the dark star, though its molecular activities have come to relative stability and impotence, still retains the enormous potentialities of molar motion; and clearly, where motion is, stasis is not.

Sooner or later, in its ceaseless flight through space, the dark

star must collide with some other stellar body, as Dr. Croll imagines of the dark bodies which his "pre-nebular theory" postulates.

Such collision may be long delayed; the dark star may be drawn in comet-like circuit about thousands of other stellar masses, and be hurtled on thousands of diverse parabolic or elliptical orbits, before it chances to collide—but that matters not: "billions are the units in the arithmetic of eternity," and sooner or later, we can hardly doubt, a collision must occur.

Then without question the mutual impact must shatter both colliding bodies into vapor, or vapor combined with meteoric fragments; in short, into a veritable nebula, the matrix of future worlds.

Thus the dark star, which is the last term of one series of cosmic changes, becomes the first term of another series—at once a post-nebular and a pre-nebular condition; and the nebular hypothesis, thus amplified, ceases to be a mere linear scale, and is rounded out to connote an unending series of cosmic cycles, more nearly satisfying the imagination.

In this extended view, nebulae and luminous stars are but the infantile and adolescent stages of the life-history of the cosmic individual; the dark star, its adult stage, or time of true virility. Or we may think of the shrunken dark star as the germ-cell, the pollen-grain, of the cosmic organism. Reduced in size, as becomes a germ-cell, to a mere fraction of the nebular body from which it sprang, it yet retains within its seemingly non-vital body all the potentialities of the original organism, and requires only to blend with a fellow-cell to bring a new generation into being.

Thus may the cosmic race whose aggregate census makes up

Plate XVIII: Norman Lockyer (1836-1920)
(Pencil interpretation of a half-tone in the *Life and Work of Sir Norman Lockyer*, said to be from a Daguerreotype of about 1856)

the stellar universe, be perpetuated—individual solar systems, such as ours, being born, and growing old, and dying to live again in their descendants, while the universe as a whole maintains its unified integrity throughout all these internal mutations—passing on, it may be, by infinitesimal stages, to a culmination hopelessly beyond human comprehension.

The Final Cosmogonic Guess of the 19th Century

Such was the conception of cosmogony of the most imaginative astronomer of his time. His book on stellar evolution, issued in 1900, marks the culmination of cosmogonic speculation in the 19th century. We shall see in due course to what extent the theory was to be accepted, and in what respects modified, by the astrophysicists of the ensuing generation. It will appear that the comprehensive cosmogonic speculation to be examined in later chapters is an elaboration, rather than a contradiction, of Lockyer's hypothesis.

To illustrate the estimate of Lockyer's hypothesis by one whose special studies at a later day give his opinion peculiar significance, the words of Professor Henry Norris Russell may be quoted.

After citing Lockyer's interpretation of the disappearance of certain spectrum lines in the hotter stars as due to the complete dissociation of calcium or iron, into "proto-calcium," "proto-iron," and the like, and his attribution of even the enhanced lines of the metals to a further dissociation of these proto elements, Prof. Russell (writing in 1928) continues:

"All this sounds amazingly modern, and it seems almost incredible that these quotations are made from a paper thirty years old, and that many of the ideas run back nearly twenty years further. The theory of ionization, and its influence upon spectra, which was first introduced to astronomers by Saha in

1922—twenty-five years later than Lockyer's summary of his long researches—has proved exceedingly fruitful, and has made good its claim at all points. Such a theory, involving as it does the electrical structure of matter, goes quite beyond the limits of the physical knowledge of 1897; but it is really extraordinary how completely, and how accurately, those features of it which were within the range of legitimate physical theory, or even speculation, at the earlier date were enunciated by Sir Norman Lockyer."

Again Professor Russell credits Lockyer with being the first to suggest the use of spectroscopic material for distinguishing between stars of certain groups, and adds that, of the four criteria suggested by Lockyer, the first is now generally recognized as a conspicuous characteristic of stars of the type referred to; the second (having to do with the sharpness of the spectroscopic lines) is basic in the methods for determining spectroscopic absolute magnitudes of the hotter stars, developed at Mt. Wilson; while the third criterion is supported by the latest work at Mt. Wilson, and the fourth can hardly be tested with existing material.

And as a concluding estimate, referring to yet another of Lockyer's heretical interpretations of spectroscopic observations this tribute is paid:

"Had Lockyer been spared for a few years longer he would have seen his identification of the various stages of the excitation of silicon confirmed by Fowler and his theory of atomic dissociations re-established in a central position in astrophysics by the work of a multitude of investigators. His fame should grow as time passes. Not least among the pioneers of astrophysics

in his observational contributions, in his insight into the true nature of its problems he stands without a rival."

XXVI

KEELER—CHAMBERLIN—MOULTON—THE ORIGIN OF THE WORLD

CENTURY marks are of course only arbitrary divisions of time. But they enter so constantly into human calculations that it is difficult not to regard them as actual mile-stones of progress. So it seems altogether fitting that a brand-new explanation of the origin of the solar system should have been one of the earliest contributions to theory and knowledge at the beginning of the twentieth century.

It is a doubly auspicious augury that the idea should have come out of America—as the first great contribution to the theory of world-making that has originated in the western hemisphere.

The new theory found its origin or at least its chief tangible support, in the observations of a famous American astronomer, Professor Keeler, then director of the Lick Observatory. This keen-eyed observer devoted the last two years of his life (1898-1900) to the special investigation of that curious member of the celestial family, the nebula. Working with the famous three-foot telescope known as the Crossley reflector, Keeler found that the universe is thickly tenanted with nebulae. He estimated that at least 120,000 of these bodies lay within the range of his vision

as aided by the three-foot mirror. Several times that number are probably visible in the five-foot reflector since then installed at the Mt. Wilson Observatory.

Of course nebulae were no new discovery. A certain number of them had been observed ever since telescopes were invented. One or two are even faintly visible like misty stars, to the naked eye. But the importance of Professor Keeler's observations con-

FIG. 79.—James Edward Keeler (1857-1900). (Crow-quilled from photograph by Brown Brothers. Original source not traced.)

sisted (1) in showing the vast abundance of these curious structures, and (2) in revealing the very striking fact that a large preponderance of the nebulae have a spiral structure. As the photographic film was made to supplement direct vision, revealing tenuosities of nebular structure that the eye cannot detect, it became increasingly evident that the spiral is, so to say, the typical form of nebulae as a class. And this suggested some

highly interesting questions as to method of world building as will appear in a moment.

Quite aside from their relation to world-making, however, these spiral nebulae are telescopic objects of peculiar picturesqueness. They seem to be great luminous whirlpools of incandescent matter. Perhaps to the average eye they suggest more than anything else the popular and familiar type of firework called the pin-wheel.

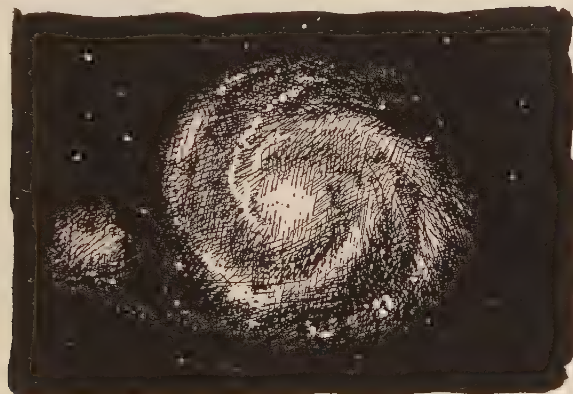

FIG. 80.—Spiral Nebula in Canes Venatici. (Crow-quilled from photograph probably made at Mt. Wilson Observatory.)

If you partially close your eyes and look at the photograph of a spiral nebula (a particularly good one is here reproduced) you can easily imagine that it represents a whirligig of fire, two revolving points making a pair of entwined incandescent spirals, and the sputtering flames sending out clouds of sparks and luminous smoke in an ever-widening circle.

Now in the point of fact, something very like this is the interpretation which the astronomer puts upon the spiral nebula. He believes that its central luminous nucleus is an incandescent gaseous body like our sun, and that the two spirals that lead

out from it, with their irregularly scattered foci of light, and their filmy veils of luminous smoke, represent matter that has burst forth from the central body, and that is now revolving upon the central axis very much as the pin-wheel revolves about its central pin.

Only of course the axis in this case is an imaginary body, like the axis of our sun or the earth's pole, and the span of the entire nebula is to be measured in unthinkable millions of miles.

There is a nebula in the constellation of Andromeda that is estimated to be so wide that light requires about fifty thousand years to span it. (This new estimate supplants the older estimate of *eight* years—illustrating the expansion of ideas in the contemporary epoch.) It is faintly visible to the naked eye.

Regardless of size, however, what gives the spiral nebula interest from the present standpoint is the fact that nebulae have long been regarded as the matrix out of which solar systems such as ours are developed.

For about a hundred years astronomers had held as stock doctrine the theory of Laplace, according to which our solar system originated from a super-heated gaseous globe which contracted as it cooled, and from time to time threw off rings of its equatorial substance that became planets.

But Professor Keeler's nebulae seemed to contradict this theory. The spiral nebulae quite obviously is not a uniformly gaseous mass. There is filmy, tenuous matter permeating its structure, but its main substance seems to be composed of more or less discrete nodules or nuclei.

The Spiral Nebula as Mother of Worlds

Professor Keeler himself noted this discrepancy, but it remained for Professor T. C. Chamberlin, of the University of Chicago, and his younger colleague, Professor T. R. Moulton,

to take the matter up, and to develop a new theory of world-making based on observation of the spiral nebula, but harmonized with all the new facts of astronomy and geology that had come to contradict the old hypothesis.

The new theory assumes that the typical spiral nebula, as revealed to us by the telescope, is in point of fact the parent structure of a solar system such as ours.

Stated otherwise, it assumes that our solar system was once a spiral nebula differing only in size from any one of the hundreds of thousands of such bodies that still tenant the universe. It further assumes that the clustered masses to be seen here and there along the arms of the spiral nebula (knots in the skein, Professor Chamberlin has suggestively called them) are nuclei out of which will ultimately develop a group of planets more or less similar to those that constitute the sun's family.

The Planetesimal Theory

A spiral nebula then, in this view, is a system of worlds in the making.

The central nucleus is the future sun. Various of the spots that lie along the arms of the spiral are the nuclei of future planets. Professor Chamberlin calls nuclei of all sizes "planetesimals" because they are supposed to be revolving in independent orbits, like miniature planets. Hence the name "planetesimal theory."

It is obvious at a glance that the larger nuclei—bigger fragments of world stuff—make up the structure of the spiral arms. It is possible that matter is streaming along these arms as it appears to be. In any case, the entire structure is revolving as if it were a solid body. The larger nuclei, however, necessarily exert a gravitational influence over the smaller planetesimals in their neighborhood; hence an incessant shower of smaller par-

ticles will fall against each larger nucleus and this augments its size and its gravitational power.

As time goes on, each of these growing nuclei will (through gravitation) suck in the matter from the space about it, as a vacuum cleaner sucks in dust, until ultimately each larger body will be revolving in a clear space.

Thus the myriads of planetesimals will have been aggregated into a small number of planets; and the spiral nebula will have been developed into a planetary system. The original central nucleus of the nebula, having drawn to itself the cloud of minor planetesimals in its neighborhood, becomes a detached central sun.

According to this theory, then, our earth, in common with its sister planets, was never a gaseous ring, nor yet a liquid globe; but was built up about a more or less solid nucleus by a perpetual meteoric bombardment.

Larger planets of our system may have gathered matter so rapidly, thanks to their greater gravitational power, as to superheat their substance to the stage of liquidity or gaseousness.

Such according to some theorists is still the condition of Jupiter and Saturn and probably also of Uranus and Neptune. Unless, indeed, Jupiter is ice-cold, as some recent heat-tests appear to suggest—which would be quite accordant with the planetesimal theory.

In any event our earth and the other smaller planets were probably from the beginning solid in structure, though doubtless developing a high interior temperature, through impact and compression. Their growth would be decreasingly rapid as the outlying planetesimal matter within their sphere was more nearly exhausted. But their growth continues, in a minor degree, even

now; for it is well known that the earth sweeps up something like a hundred million meteors each day,—these meteors being, supposedly, belated fragments of the original spiral nebula.

Occasionally a larger fragment of world-stuff in the form of a giant meteorite falls into our atmosphere and finds at last a resting place on the earth.

FIG. 81.—Jupiter (Redrawn from photo by Dr. E. C. Slipher.)

The Disconcerting Conduct of Phœbe

"Give a dog a bad name and you soon hang it," says the old proverb. It seems to be much the same with a theory. Once you challenge it with a discordant fact or two, new evidence against it begins to crop up on every side. So it is not strange that just as Professors Chamberlin and Moulton were challenging the theory of Laplace, a very striking piece of evidence against the theory should have been brought to light from a quite unexpected quarter.

The new evidence was secured by another American astronomer, Professor W. H. Pickering. While examining a star photograph made at the observatory established by Harvard University at Arequipa in South America, Professor Pickering noticed a hitherto undescribed minute star lying in the neighborhood of the planet Saturn.

He strongly suspected it of being a new satellite.

Fig. 82.—Professor W. H. Pickering Studying Star Negatives. (Crow-quilled from Brown Brothers' photograph.)

But he had not the time to follow up the course of the little body at the moment, and it was not until 1904 that he rediscovered it, and by noting its shift of position from night to night, proved that it is really a far-outlying moon of Saturn.

To this new found niece of old Mother Earth, Professor Pickering gave the name of Phoebe.

Now Saturn was already known to be provided with an abundant family, eight moons having previously been recognized in addition to the unique system of rings. Therefore the advent of this ninth satellite would not have created any great sensa-

tion in the astronomical world had it not been made evident that Phoebe is behaving in a most anomalous manner. Not only has she taken up her position at a vast distance from her parent orb, but she is actually revolving in opposite direction to the direction of rotation of Saturn and the orbits of revolution of all the other moons.

A tenth was believed to be discovered a little later (1905) by Professor Pickering but this discovery has not been confirmed.

It will be recalled that according to the hypothesis of Laplace each satellite has been spun off from the equatorial belt of its parent planet, and hence must obviously go on revolving in the direction of the parent body's rotation. Our moon follows this rule; so do the four moons of Mars, the five moons of Jupiter that were then known, and the eight previously known satellites of Saturn. The rings of Saturn had also been proved to spin about in the same way; indeed, the system of Saturn had often been pointed to as in itself presenting what might almost be called a working model of the Laplacian hypothesis of worlds in the making.

And now comes this ninth satellite, like a broken cog in the wheel, to interfere with the harmonious arrangement of this pleasing mechanism. Phoebe is but an inconsequential body as to mere size. And she is so distant from us that, as Professor Poor estimates, to see her at all puts a test on our telescopes equivalent to what would be required if one were to stand in New York and attempt to watch a humming bird flitting about the flower beds in the garden of the Capitol at Washington.

Yet this one tiny satellite moving in reverse order seemed to disprove the entire theory as to the origin of worlds.

For, be it understood, exceptions do not prove rules in the

scientific world—they disprove them. This single refractory little satellite would upset the nebular hypothesis more convincingly than all Professor Chamberlin's reasoning—unless a way could be found to explain its anomalous conduct.

Has the World Turned Upside-Down?

But mathematicians are resourceful in sustaining accepted hypotheses, and of course the old theory was not to be given up without debate. More than one explanation was put forward that might conceivably account for Phoebe's eccentricity.

In particular Professor Pickering himself explained it picturesquely by assuming that Saturn had originally rotated in the reverse direction, but that subsequent to the detachment of the ninth satellite the planet had turned completely over owing to what is called the processional effect of the sun's gravitational pull on its bulging equator, which acted as a sort of tidal brake.

You can illustrate the effect very clearly if you will experiment with a kind of top or gyroscope that whirls in so-called gimbal rings.

This top will spin for a long time without changing its direction of axis if not interfered with.

But if you touch your finger to its rim (tidal brake) you will cause it to twist to one side, and as you continue the pressure you will see the top turn completely over and remain there (the obstruction being removed) spinning in the opposite direction to that which it had at first.

This interesting theory of the overturning of the planets applies of course to other members of the system, including the earth.

It finds partial support in the vertical revolution of the satellites of Uranus.

But another complication was introduced when Professor Per-

rine in 1905 made photographic discovery of two new moons in the system of Jupiter (the sixth and seventh) which seemed to be revolving in almost the same orbit, but one of them going forward, the other (No. VII) in retrograde direction.

Subsequent observation did not confirm the retrograde movement of the seventh satellite. But in 1908 Melotte at Greenwich discovered an eighth satellite, and a ninth was discovered in 1914 by Nicholson at Lick Observatory, and both of these are retrograde. These outer satellites could not be accounted for by the old theory. Then there remain such anomalies as the exceedingly rapid rotation of the innermost moon of Mars; the ever-puzzling fact that neither the sun itself nor any of the planets revolves fast enough to produce a centrifugal effect adequate to overcome the attraction of gravitation; and the vital fact that the planets do not revolve in the plane of the sun's equator.

So even the bizarre theory of overturned planets would not avail to rescue the nebular hypothesis.

Moreover Professor Moulton in 1909 carried out an elaborate mathematical investigation which seems to render it at least doubtful (1) whether a revolving gaseous body, such as the original Laplacian nebula is supposed to have been, could develop the mechanical conditions necessary to whirl off a ring of its substance, and (2) whether such a ring could assume the form of a planet even if it were detached.

The Planetesimal Theory Solves Many Puzzles

The planetesimal theory, on the other hand, seems to afford a fairly satisfactory explanation of all the observed anomalies of planetary revolution and rotation, without doing violence to any recognized law of mechanics.

For example, the crucial facts that the sun rotates slowly and that the planets do not revolve in the plane of the sun's equator,

present no difficulties, since neither the direction nor the speed of the sun's rotation is conceived as having had anything to do with the genesis of the planetary system.

The sun merely continues to rotate—like the big top that it is—on the same axis and with a good deal the same speed that it had before the explosive outburst occurred which produced the spiral nebula out of which the planets have developed.

The planets themselves, as they were built up about nuclei or masses in the spiral nebula, might at first have no motion of rotation, but would begin to rotate in response to the influence of impinging planetesimals.

Professor Moulton shows that the results of such impingement would be generally, but not necessarily, to give a forward rotation somewhat in the plane of revolution. But the presence of other large masses (future moons) near by may alter this; and there is no theoretical reason why any degree of aberration might not be observed. Thus the variously tipped axes of the planets are accounted for.

Again, outlying masses that were not at first part of a given planetary system might be brought within the influence of a forming planet at a relatively late stage (somewhat as Jupiter even now captures comets), and these captives might revolve in any plane or in any direction, just as comets do. So the retrograde revolution of Phoebe is explained; also the aberrant revolution of the moons of Uranus and Saturn. Likewise the speed of Little Phobos, which races three times round Mars while that planet is revolving once.

There is no restriction put upon the speed of a satellite by the rotation speed of its primary according to the new theory.

It may be added that Professor See of the Marine Observatory

at Mare Island, California, has elaborated this capture theory, in particular with reference to the asteroids, which he thinks were drawn into their orbits by Jupiter. Our moon also he regards as a capture product. Its curiously marked face, he thinks, shows the effect of the impact of asteroids as it came through their zone. Each lunar crater, in his view, marks the tomb of a planetoid, and not the location of a former volcano.

The planetoids themselves, by the way, were always stumbling blocks to the Laplacian hypothesis. In the new view they are simply largish planetesimals that did not chance to lie near a larger nucleus or condensation and hence have remained isolated, like myriads of the yet smaller fragments we call meteorites.

In a word, then, the planetesimal theory seems to have a high degree of probability. It is easily the most plausible hypothesis of the origin of the solar system that has ever been advanced. It is peculiarly hospitable to various interpretations as to details of progression in world-making. No known fact of astronomy or mechanics contradicts it vitally; a multitude of facts support it.

Of course it is not utterly nugatory of all that went before. We have seen that the new theory, like the old, conceives the solar system to have originated from a nebula—it is still a "nebula" hypothesis.

But the entire change of view that it contemplates in regard both to the original state of the nebula and the stages of evolution through which a planetary system is evolved, is so radical that the theory is fully entitled to be regarded not only as novel but in a sense as revolutionary. It extends to the planetary system in detail the principles of world-building made familiar through Lockyer's famous meteoritic theory of sidereal cosmogony.

The Origin of Spiral Nebulae

If, then, we give at least provisional recognition to the spiral nebula as the "Mother of Worlds," a question naturally arises as to how this interesting structure itself came into being.

Professor Moulton answers this question in detail. He tells us that what we now view as a spiral nebula was aforetime (let us say a billion or a hundred billion years ago) a gaseous star, not particularly different from millions of others that exist in the sky today, or for that matter from our sun itself.

But it chanced that in its progress through space this star flew in a direction which brought it ultimately in the neighborhood of another star. Unless the scheme of the universe is something quite different from what we now imagine, this must happen in course of time to every stellar body. All the stars are moving, and their rate of speed in terms of modern measurement may be scores of miles, even hundreds of miles, per second. They are moving in different directions, in groups, clusters, pairs, or singly, and it would seem inevitable that their paths must cross.

It will not often happen, in all probability, that two stars will meet head on. But they may exert a tremendous mutual influence without actually colliding. A French astronomer named Roche made, about 1850, a very notable estimate to the effect that if two stellar bodies of unequal size approach each other within a distance of about two and a half radii of the larger, the power of gravitation will suffice to tear the structure of the smaller body asunder.

To make the illustration specific, if a body as large as the moon were to come within something less than 10,000 miles of the earth, the small body would explode like a bomb and its fragments would be scattered out into space. This critical distance

of two and a half radii (more exactly 2.44) is known to astronomers as Roche's limit.

Saturn's rings lie within this limit, and seemingly illustrate the law, as they consist of comminuted particles of world-stuff.

But suppose now that two stars hurtling through space approach each other at such an angle as not to come within the dangerous explosion zone (Roche's limit) but, on the other hand, near enough to exert a mutual tidal strain of tremendous power. Gigantic tides will then be raised on each of the bodies, and even though their structures as a whole are not disrupted, there will be a vast eruption of their gaseous substance from opposite sides of both bodies.

That the tidal effect should be manifested equally in opposite directions, is well understood by mathematicians. To the non-mathematical mind, the fact, though puzzling, is made familiar by the twice-daily recurrence of the ocean tides.

If we look closely at the photograph of a spiral nebula, we shall see that the two spiral arms do in point of fact originate exactly opposite each other in the structure of the globular central nucleus.

The eruptive mass which thus burst forth with explosive violence from each side of the star would stream straight out into space in opposite directions and each stream would ultimately fall directly back upon the body from which it came, as a ball drops back to the earth when you toss it into the air, were it not that the gravitational influence of the passing star, which caused the eruption, continues to make itself felt upon the erupted matter. The main eruption would occur just at the moment when the stars were nearest each other, minor eruptions would have taken place while the stars were approaching and will continue

for some time as they recede. And all the matter both of major and minor eruptions will be drawn aside from a direct outward flight by the gravitation pull which shifts its direction constantly with the movement of the passing body.

The result will be, as Professor Moulton has demonstrated mathematically, that the two main eruptive streams will be drawn out to form independent spirals, the space between which will be more or less filled with matter from the minor eruptions; and that each particle of eruptive matter will ultimately settle into an elliptical course, for the most part permanently detached from the central nucleus.

In other words, such a form as we see actually taken by the spiral nebula is fully accounted for.

BOOK VII

THE NEW HEAVENS

"If the stars should appear one night in a thousand years, how would men believe and adore; and preserve for many generations the remembrance of the city of God which had been shown! But every night come out these envoys of beauty, and light the universe with their admonishing smile."

—*Emerson.*

XXVII

THE NEW HEAVENS

> Lift up your eyes to the heavens, and look upon the earth beneath: for the heavens shall vanish away like smoke, and the earth shall wax old like a garment.
>
> *Isaiah—LI*, 6.

THE heavens shall vanish away like smoke. A prophetic vision! After something like three thousand years, the telescope of the astronomer has made it a reality. The *old* Heavens have indeed vanished. What would Isaiah say could he come back to learn the manner of their vanishment?

I shall not attempt to answer that question. But I wish briefly to summarize some salient aspects of the contemporary view of the new heavens; in particular to review in the briefest manner the essential aspects of new knowledge revealed by contemporary star-gazers and their associate workers, and to interpret the bearings of the new revelations on questions of cosmology and cosmogony.

Never was there greater activity in the field of astronomy than in our generation. Never before were so many men engaged in the investigation of one aspect or another of the multifarious problems that confront the watcher of the skies. Were we to attempt merely to glance into all these fields, the result would be confusion rather than clarification. We must be content to select a few salient aspects, not, perhaps, because they have

greater importance than other aspects, but because they bear more directly upon the larger problems of the origin and destiny of the universe.

Stated otherwise, problems that concern the evolution of the celestial mechanism; the origin of the world-system; the sequence of changes signalizing the life-history of a star.

In particular we must ask whether the astronomer of our day is prepared to write a new story of the creation of the universe in lieu of the abandoned one, and to make a new forecast as to the future history of the universe in general and the solar system in particular.

That would be a large order if one contemplated an exhaustive treatment.

But for the outline here contemplated (presented in part by way of recapitulation) it is not so formidable. Perhaps it may not lead us to results as conclusive as we might desire. As to that, we shall see what we shall see.

Old Ideas and New

At the outset, let it be recalled that only a few things at most that could in any proper sense be called new and original are achieved in any single generation.

The seemingly new ideas and discoveries that gain prominence in any age, are almost without exception—as the history of science reveals—merely old ideas revived, rejuvenated, and forced into view of a generation whose predecessors had refused to receive them.

Thus it was that even the revolutionary conception of Copernicus had been anticipated by Aristarchus in the old Greek days; the Nebular Hypothesis of Laplace was but a mathematical elaboration of the unaccepted nebular hypothesis of Kant, who had also amazing prevision of a theory of the slowing of the earth's

rotation by tidal influence which has only been revived in our own day.

The newest conception of the spiral nebulae as "island universes" far beyond our galactic system, but restates the case as it was put forward by the elder Herschel, who in turn borrowed it from Kant (the same immortal philosopher already twice mentioned), just as he borrowed his "grindstone theory" of the universe (now again at the fore) from another of his predecessors, Thomas Wright.

It is no disparagement to present-day workers, then, to say that their tasks are for the most part not new.

On the other hand, it would do less than justice to the work of some of them were we not to recognise that, as words are ordinarily used, their contributions are essentially original.

For example, the classic work of Langley and Abbot on solar radiation, carried out with that necromantic instrument, the bolometer; the spectacular achievements of Campbell and Boss and Kapteyn in the observation and interpretation of the movements of stars; the laborious and brilliant work of Pickering and his successor Shapley and their associates in the spectroscopic survey of the heavens; the weirdly penetrating scrutiny of the sun by Hale; and the exploration of the depths of space with giant telescopes by the associates at Mt. Wilson; the dazzling measurement of the diameter of a star by the interferometer of Michelson; the paradoxical interpretation of the universe by Einstein; and the penetrative cosmogonic speculations of Chamberlin and Moulton, of Hertzsprung and Russell, of Sir James Jeans, and of Prof. A. S. Eddington.

We have caught glimpses of the work of each of these investigators, and shall see more of some of them, as well as of several

other contemporaries in the attempt to fulfill the purpose above outlined.

Technique of the New Astronomy

Of course the contemporary astronomer has for the most part ceased to be a "star-gazer" in the literal sense of the word.

He uses telescopes, to be sure, but he has the aid of artificial eyes, in the form of spectroscope, spectroheliograph, and photographic plates.

There was a time when the maker of star-charts gazed hour after hour through the tube of his meridian circle, and made his record by pushing a button when an individual star crossed the line of the spider web that bisected his field of vision.

Now a few photographic plates exposed in succession record the positions, more accurately than the unaided eye could possibly do, of more stars than any individual worker could observe with accuracy in a lifetime.

Then there are modern tricks of technique that give opportunity for comparisons of star positions until recently undreamed of.

Thus the campaigner who goes in quest of records of a planetoid or of Mars for parallax purposes, makes two exposures on the same plate, at intervals of a few hours, slightly shifting the position of the plate in order that the stars may not be exactly superimposed, and subsequently makes his observations in the laboratory by meticulous measurement of the planet's changed relations to the stars in its neighborhood.

Again a plate may be exposed, for minutes or hours, in the focus of a great telescope directed toward the infinite hosts of stars; then removed from the telescope and stored away undeveloped, to remain for perhaps ten years before it is taken out and again adjusted for observation of the same field. After

this second exposure, the plate is developed, and the double images of thousands of stars, lying side by side, will show the patient laboratory searcher whether individual stars or groups of stars have shifted their positions anomalously, thus revealing "proper motion."

What would Halley, who first detected the "proper motion" of three stars through study of ancient and contemporary charts have thought of this? What would Herschel have thought, who detected the line of flight of our own solar system through study of the proper motions of the half dozen stars whose records were available?

Need we wonder that the contemporary star-searchers, with such mechanical aids, have been able to detect the lines of movement of thousands of stars, and thereby to gain at least a general impression as to the aggregate movement of clusters, groups, and even gigantic streams of the migrating hosts of our galaxy?

It was thus that Prof. Lewis Boss, of Albany, learned the secret of about forty stars in the constellation Taurus, between the Pleiades and Aldebaran that are moving through space together in parallel lines at uniform speed, like a flock of birds.

Some General Results

It was thus that Jacob Cornelius Kapteyn, the Dutch astronomer, discerned that vast numbers of stars of our galaxy are moving in two great streams, almost in opposite directions, seemingly bound for goals beyond our universe. It was Kapteyn, indeed, who first suggested the method of observation by double exposure of a photographic plate.

After he announced his discovery, in 1904, the conception of the stellar universe as a chaos of stars, each with its own independent motion in space (as Prof. W. M. Smart has phrased it) was effectively disposed of. The conception that the chief

mass of stars of our galaxy is revolving about a uniform center, like the structure of a spiral nebula, was however, rendered doubtful. At all events, it was made clear that there are great groups of stars that do not partake of such a motion.

In recording the movements of the stars, the photographic plate, adjusted merely in the focus of the telescope, has obvious limitations. It can tell us nothing as to line-of-sight movement.

But here the spectroscope takes up the story. In the service of various workers, notably Prof. W. W. Campbell, of Lick Observatory (later President of the University of California), it yielded amazing records of the movements of a multitude of stars. The lines of the spectrum are shifted toward the violet if a star is approaching, toward the red if it is receding (the so-called Doppler effect). Records thus secured supplement the cross-flight records of the ordinary negative.

Taken together, they have gone far toward revealing the structure of the stellar universe.

What would old Hipparchus and Ptolemy have said could they have witnessed the stars of their outermost fixed sphere of the heavens hurtling hither and yon? What would the Arabian star-gazers and their European successors to the time of Tycho have thought, could they have seen the glassy sphere in which they conceived the stars to be imbedded, shattered into myriad fragments by the mad rush of stars by millions upon millions (where they conceived the total number in existence to be but a few thousands), dashing at an average speed of perhaps twenty miles per second—some of them ten, twenty, perhaps even a hundred or a thousand times that?

Verily, the old heavens have vanished, even as Isaiah pre-

dicted—though the new heavens are perhaps not precisely the firmament that his prophetic eye envisaged.

Let us survey with the contemporary astronomers some salient aspects of the new heavens.

XXVIII

THE EROS CAMPAIGN OF 1900—PERFECTING THE SOLAR YARD-STICK

IN THE year 1900 various bands of astronomers, equipped with a score or so of photographic telescopes, set out on what was whimsically dubbed the Eros Campaign. Being interpreted, this means that the astronomical bodies of the world went gunning for an inoffensive planetoid named Eros.

Planetoids, it will be recalled, are very small members of the sun's family, which circulate, like a shower of meteorites, in the otherwise vacant space between the orbits of Mars and Jupiter. It will be recalled, further, that the first of these little planets to be discovered was found, by chance, on the first day of the 19th century, and that thereafter the discovery of planetoids was the avocation of many astronomers in odd hours.

After the use of the photographic plate made detection of the planetoids relatively easy (these bodies making a dash on the plate which reveals stars as dots), so many planetoids were in evidence that for the most part astronomers no longer bothered to give them names, but were content to number them.

When the number reached the thousand mark, exception was made, for sentimental reasons, and the next three planetoids discovered were very appropriately christened Piazzia, Gaussia and Olbersia in commemoration of the three distinguished astronomers associated with the first discoveries of minor planets —the Italian observer, Piazzi, who saw the first planetoid; the German mathematician, Gauss, who gave the formula that enabled astronomers to find it again after it was lost; and the physician-astronomer Olbers, who made the second planetoidal discovery.

Mr. Hoover's Particular Planet

The quest of planetoids continuing, and a few astronomers rather specializing in this field, the number of little bodies observed has increased so rapidly that it is hard to keep track of the statistics, the 1930 census being of the order of two thousand.

It is interesting to note that one member of the family, discovered by a Viennese observer in 1928, was given the name Hooveria, in honor of the American Food Commissioner who had endeared himself to Europe, and who subsequently became president of the United States.

It will further be recalled that the discovery of the first planetoid, christened Ceres, deprived the old seven-day myth of its significance, by giving an eighth planet to the solar system. In due course, the discovery of Neptune, of the major series, followed; and, as we have just seen, the name of the minor planets soon was legion.

If in our day a new mystic were to revive the planetary tradition, the new sacred number would be, perhaps, 2009—2008 days, let us say, for Evolutionary Creation, and the final day for rest.

The not unamusing reflection presents itself that, if we count each "day" as a million years, the New Creation story, based

on the new planetary symbolism, would ascribe to the earth about the same age which is accorded it by the best accredited estimates of present-day astronomers and geologists.

Eros and the Solar Yard-Stick

But enough of reminiscence. We have come to the planetoids for a quite different purpose.

Our present concern with them is not with the group of two thousand, but with a single member, the one named Eros.

This little body, discovered in the year 1898, stands out among all the rest for the sole reason that its exceedingly elliptical orbit brings it, on occasion, nearer to the earth than any other planetary body ever approaches. And thereby hangs the tale I wish to tell. It concerns the highly important matter of the accurate survey of the entire solar system.

It is through studies of Eros, made during the "campaign" to which I referred at the outset, that the most recent and most accurate estimate of solar-system distances has been made.

Before we inquire just how this was accomplished, let us for the moment envisage (by way of recapitulation) the conditions of astronomical measurement as applied to the sun and its neighbors.

The yard-stick of the solar system is a line joining the center of the earth and the center of the sun.

To be slightly more accurate, it is the *average* distance of the earth from the sun—for of course the actual distance varies with each sector of the elliptical orbit—being greatest at Aphelion (summer solstice) and least at the opposite end of the circuit. At the periods of the equinoxes, the distance is intermediate.

The unit distance for solar measurements, is the calculated mean distance—what would be the radius if the earth's orbit were circular.

The convenience of such a yard-stick for measurement of the distances of the planets is obvious.

It is rather odd that, after more than two hundred years of testing, there should still be doubt in the minds of astronomers as to the exact length of this yard-stick itself. In particular this seems odd, when we reflect that there are at least a dozen methods of measuring the yard-stick, and that concerted efforts have been made from time to time by the astronomers of the world to make the measurements accurate.

The explanation, however, is merely that astronomers are accustomed to demand extreme accuracy in their measurements of all types. There has been no question at all for several generations as to the approximate length of the earth-to-sun yard-stick. The distance has long been known to be *about* 92,870,000 miles. The question at issue concerned only the odd thousands of miles by which the length of the yard-stick departs from the round number.

It was to test this refinement of measurement that the "Eros Campaign" of 1900 was undertaken.

The Eros Campaign

As already intimated, the offensive weapon in this campaign was the camera. The object of the campaigners was to photograph from different points of view the region of the heavens in which Eros appears at the time of its nearest approach to the earth. Eighteen photographic outfits, variously located, were devoted to this purpose. A large number of highly satisfactory photographs were taken.

What then? Well, now comes the strangest part of the story. These photographs, individually and collectively, to casual inspection reveal nothing of the slightest significance.

They are simply ordinary-seeming star-charts, consisting of the usual black background dotted with points of light.

Of course one of these points of light, in each photograph, is the image of the little planet Eros. But that, though of course an essential feature of the photograph, tells nothing to the casual inspector. The work of measuring the yard-stick had only just begun when the photographs were completed, the plates developed, and the entire series placed in the hands of Mr. A. R. Hinks, of the Cambridge Observatory, who was to be responsible for the "coordination and discussion" of the Eros observation.

His task was to sit down with those negatives and measure them, and make calculations from his measurements, day after day, week after week—and in the aggregate year after year.

As to the measurements, it is recorded that on the Cambridge plates the displacement of images is of the order of one-twentieth of an inch. The mathematical calculations involved are much longer—best measurable in terms of months.

If astronomical workers were given to a popular type of illustration, we might learn how many times round the globe the formulae used by Mr. Hinks in solving the Eros puzzle would reach if laid end to end.

The Solar Parallax

A gruesome task, the average layman would think it. But for a mathematical astronomer, a task fraught with allurement. Probably it was with a sigh more of regret than of relief that Mr. Hinks finally brought his calculations to an end, and was able to announce that the "angle subtended at the sun by the earth's radius is 8.807 seconds of arc."

This "fundamental angle" is called the solar parallax. It represents the angle of the lines from the ends of the earth's radius meeting at the center of the sun.

As the length of the earth's radius, which thus makes the third side of a triangle, is definitely known, it is a relatively simple problem in triangulation to translate the parallax into terms of distance in miles between the earth and the sun—which is the yard-stick we are all along seeking.

This distance was found to be, in round numbers, 92,900,000 miles.

The New Measurement Confirms Old Ones

As already explained, the distance in question is the average or mean distance.

This newest measurement does not conspicuously change the estimate hitherto accepted, based on multitudes of measurements by different methods—including, prominently, observation of the transit of Venus across the face of the sun, calculations from observation of the occultation of the moons of Jupiter, observations of Mars (in particular by Gill in 1877), heliometer observations of the minor planets Victoria and Sappho: calculations based on the "Constant of Aberration" of light, studies of the parallactic inequality of the moon, and spectroscopic measurement of the earth's orbital speed.

The distance 92,876,000 miles, resulting from a study of the constant of aberration, was held by Young to be on the whole perhaps the most accurate measurement available a generation ago; this being the equivalent of the parallax 8.803.

It will be seen that the newest measurement varies from this by only 4-thousandths of a second of arc.

The Paris conference of 1911 adopted 149,450,000 kilometers (92,870,000 miles) as the most likely value for the mean distance in question. Mitchell and Abbot, writing in 1927, give 92,870,000 miles as the generally accepted value—a parallax of 8.80.

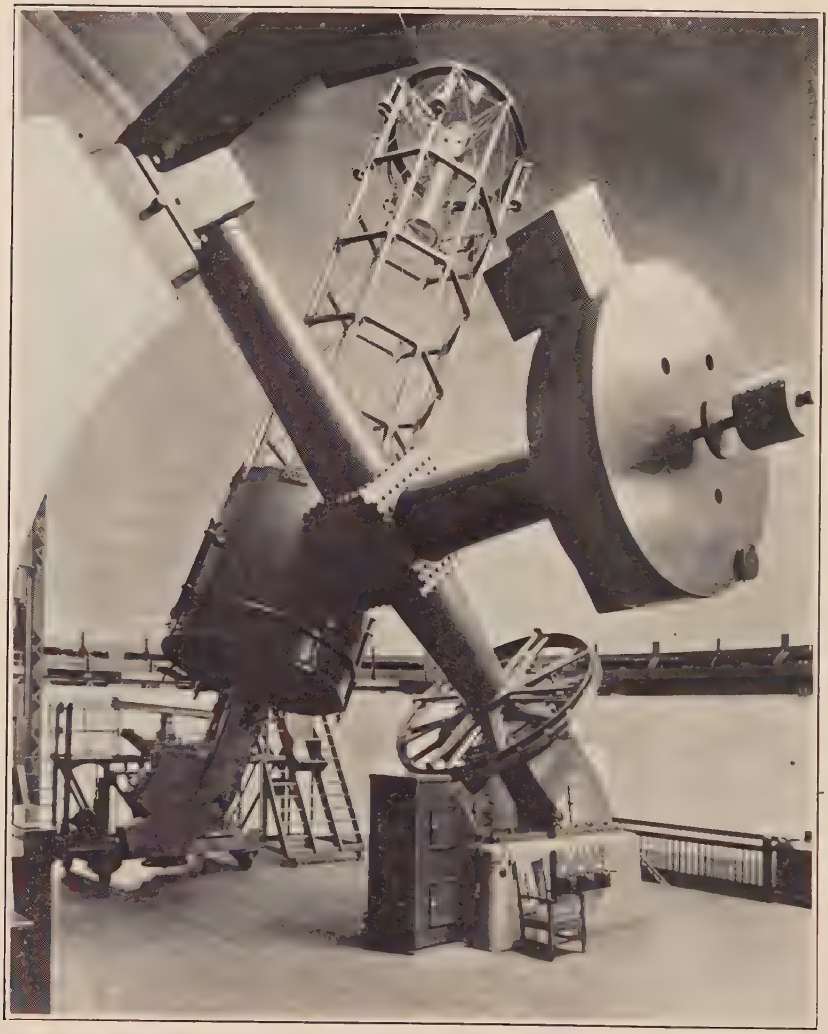

Plate XIX: The 72-inch Reflector of the Dominion Observatory

Inasmuch as Newcomb as long ago as 1896 adopted 8.797, plus or minus 0.007 seconds, as the value of the solar parallax to be used in the planetary tables, while Harkness in 1891, at a discussion of many measurements, adopted as the final value 8.809 seconds, plus or minus 0.006, it will be seen that the newest measurements, based on study of the images of little Eros, do not differ significantly from the earlier estimates.

Fig. 83.—Charles Augustus Young (1834-1908). (Crow-quilled from original photograph by William Henry.) Preparing to take spectroscopic records of the solar eclipse of 1900.

There was, indeed, a divergence of only a small fraction of a second between nine groups of estimates collated by Newcomb, in which the measurements of 19th century astronomers were recorded.

We may feel fairly confident, then, that if an airplane capable of achieving an average speed of one thousand miles an hour were to set out for the sun, it would have an average journey ahead of 92,870 hours.

It must be recalled, however, that on January 1st, the earth is about 3,000,000 miles nearer the sun than on July 1st.

At first blush, that would seem to suggest that the voyager would do well to plan his journey for the winter season, but when we reflect that, even at a speed of a thousand miles an hour, almost twelve years would be required to reach the goal, the time of starting seems less important.

Uses of the Yard-Stick

In astronomical work there are no endings, but only new beginnings. So we learn without surprise that expeditions were early fitted out for a new Eros campaign, for the years 1930 and 1931, when the little planet approaches the earth to within about 14,000,000 miles, giving opportunity for even better measurements. It will probably be necessary in the course of another decade, after the measurements are evaluated, to revise slightly the estimate of the solar yard-stick.

There is no probability, however, that the change will be significant for any one but the technical student of solar distance.

A concluding word as to why this yard-stick has all along been considered so vitally important. The reason is almost adequately implied in the characterization of the mean solar distance as a "yard-stick." But to get its full significance, one must understand that the measuring unit can be applied to all members of the planetary family in a very curious way.

It will be recalled that Kepler's third law establishes a certain relation between the orbits and distances of all members of the planetary family. This made it possible to establish the relative locations of the planets—to draw a true chart, to scale, of the entire planetary system as then known—before any actual measurement has been accurately established.

It follows that when any particular interval of the scale could be determined in miles, all other distances were at once revealed, as it were automatically.

It is precisely the case of an ordinary terrestrial map, say of the United States, in which the boundaries of the States are accurately drawn, so that relative sizes are revealed at a glance, or more accurately by measurement, but where there is no clue to the actual size of any State, unless (as is usual) down at the corner of the map a "scale" is given which supplies the interpretation.

Seeing that one inch, say, represents a hundred miles, you can promptly determine the distance from New York to Chicago, or any other distance that may interest you.

Similarly with the chart of the solar system. When you know the distance between the earth and sun, all other distances may be at once measured.

Of course any other planetary orbit might have been adopted as the unit scale. We use the earth-sun yard-stick merely because we are residents of the earth, and naturally view the planetary system from our own coign of vantage.

XXIX

SCHWABE—HALE—EDDINGTON—THE NEW SUN

AWAY back in the year 1857, the Gold Medal of the Royal Astronomical Society of England was awarded to a middle-aged apothecary of Dessau, Germany. The name of the recipient was Samuel Heinrich Schwabe. The work for which he was honored was the study of sun spots.

It appeared that the apothecary had early developed a penchant for observing these blemishes on the face of our luminary, the discovery of which by the first users of telescopes two centuries earlier had so disturbed the equanimity of the Aristotelians of the period. Aristotle, it will be recalled, had conceived the sun as a perfect body; assuredly unmarked by blemishes of any type. His doctrine accorded with the ecclesiastical conception of the perfection of all heavenly bodies.

How great was the shock to all lovers of tradition when the perfect body was seen to be pock-marked, can be fully appreciated in our iconoclastic generation only by active use of the imagination.

But horror gave way in due course to indifference, and for a good many generations no one paid any particular attention to the spots on the sun, beyond noting casually that they were sometimes more and sometimes less abundant—appearing and disappearing without seeming rime or reason—and that by observing them one could discern that the sun revolves on its axis in a period of about twenty-six days.

About the middle of the 19th century, however, it was discovered by Lamont, of the Munich Observatory, that there is a periodicity in the phenomena of earth magnetism, and that the fluctuations are singularly in accord with fluctuations in the number of sun spots.

The fact that the earth's magnetic pole is not at the geographical pole had long been known; also that there are daily fluctuations in the exact direction of the needle's pointing. Lamont's discovery was that these fluctuations increase and decrease with fair regularity in a period practically identical with the sun-spot period.

In the following year, 1852, it was pointed out independently by three observers that the maximum deviation of the magnetic needle occurred in periods of greatest sun-spot abundance.

Belated Recognition for the Apothecary-Astronomer

Such association between a seeming defect in the sun's constitution and a curious anomaly of one of the least understood phenomena of our planet, naturally excited general interest in the scientific world. Then it was, and apparently not before, that scientists in general began to inquire just who was responsible for the knowledge of periodicity of the sun's spots.

The answer brought to the front the apothecary of Dessau, whose queer avocation hitherto had been, it appeared, its own reward. Now, at the hands of the Royal Astronomical Society the zeal of this amateur was to receive more tangible recognition.

In presenting the medal, the president of the Society pronounced this well-merited encomium:

"Twelve years hath Schwabe spent to satisfy himself—six more years to satisfy, and still thirteen more to convince, mankind. For thirty years never has the sun exhibited his disk above the horizon of Dessau without being confronted by Schwabe's imperturbable telescope, and that appears to have happened on an average of about three hundred days per year. This is, I believe, an instance of devoted persistance unsurpassed in the annals of astronomy. The energy of one man has revealed a phenomenon that had eluded even the suspicion of astronomers for two hundred years."

Once more the amateur in astronomy had triumphed—as Horrox and Bradley and Herschel and Olbers had triumphed.

In particular, one recalls Horrox, the devoted young clergyman because he also achieved fame by observation of the sun—even of a spot on the sun, though in this case the spot was

not a local blemish, but merely the silhouette of the planet Venus shadowed against and creeping across the face of the great fire-ball.

There the comparison ends, for the English clergyman had made his observation in a brief term of hours of one day; whereas the apothecary of Dessau required for his discovery a long term of years. The English amateur died at the age of twenty-two; the German amateur had attained the age of sixty-eight before his labor of love, then of more than thirty years' duration, gained recognition.

Periodicity of Sun Spots

Schwabe's observations revealed maximum groups of sun spots at intervals of about ten years. Subsequent investigations, in which reports of earlier observers are included, give an average period of slightly over eleven years. There is, however, a considerable variation. Periods of maximum spots sometimes are two years ahead of schedule.

It developed, also, that there is a typical and curious distribution of the spots, inasmuch as they are seldom seen within five degrees of the solar equator, nor in latitudes higher than thirty-five north or south. The beginning of a new cycle after a time of freedom from spots, shows an eruption in or near latitude thirty-five, according to the researches of Carrington, whence, year by year, they invade lower latitudes, like a spreading eruption on the face of a measles-patient.

Observation of the movement of spots at different latitudes appeared to show that the sun rotates in about twenty-five days, but that the fluid character of its constitution permits the spots at higher latitude to lag behind, accomplishing their circuit of the sun in a period of about twenty-seven and one half days.

These tangibilities were known, while the nature of the spots

remained an entire mystery. Further knowledge was not forthcoming until a new instrument called the spectroheliograph was available. The basic idea involved occurred independently about the year 1890 by Dr. G. A. Hale, whose work at Mt. Wilson was to make him famous, and the French astronomer Deslandes.

This instrument invented by Dr. Hale, adjusted to a telescope, performs feats of wizardry in the interpretation of the sun's surface, spots included, which were quite unpredictable.

The spectroheliograph travels across a plate, receiving light only through a narrow slit. In effect it photographs the light of a single line of the spectrum. The result is a picture in no way resembling anything that could be produced by the ordinary exposure of a photographic plate.

Magnetic Sun-Spots

Among the most surprising discoveries made by Dr. Hale in the course of his varied studies of the sun's surface was that sun-spots are fields of localized magnetic influence.

It had for a good while been believed that sun-spots represent virtual craters in the sun's substance, due to localized explosions of extravagant dimensions. The spectroheliograph confirmed this idea, and added the highly interesting information that the uprushing vapors take on a whirling motion, and may therefore be likened to cyclones in the earth's atmosphere.

It was observed that those cyclones occurring in the sun's northern hemisphere usually have a clock-wise rotation; those in the southern hemisphere having anti-clockwise rotation; thus corresponding with the normal direction of cyclonic air currents on the earth. There are, however, exceptions to the rule.

In the study of these solar cyclones, Professor Hale was led to notice a spectrum effect which seemed to him to suggest that

the light coming from the sun-spots shows the influence of electrical and magnetic forces.

Specifically, what was noted was that the lines of the spectrum seemed to manifest the Zeeman effect.

This is a phenomenon that derives its name from having been first observed and described by Professor Zeeman of Amsterdam in 1896. His observations had nothing to do with the sun, but were made in the laboratory with the aid of an ordinary flame and a powerful electromagnet.

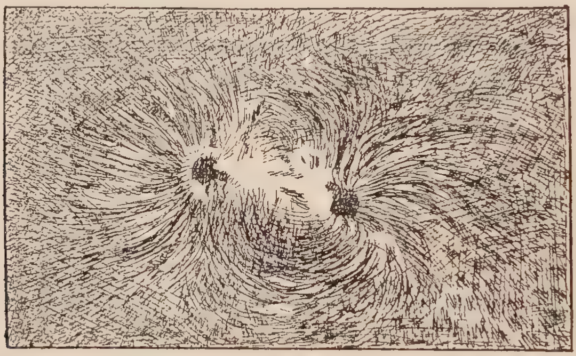

FIG. 84.—Spectroheliograph of Sun-spots. (Crow-quilled from half-tone in Abbot's *The Earth and the Stars*.) Original taken with 13-foot spectroheliograph at Mt. Wilson, by L. H. Humanson, photographed in red hydrogen light.

The essence of his observation was this: When an incandescent substance is placed in the field of an electromagnet, each of the lines representing that substance in the spectrum is split into two or more lines.

If the rays of the light which produce the spectrum are parallel to the lines of force of the magnetic field, spectrum lines are divided into two lines, each of the new lines consisting of light that is said to be circularly polarized.

If, however, the rays of light producing the spectrum are transverse to the lines of magnetic force, the spectrum line is divided into three lines, the central one occupying the original position, and the lateral ones being plane polarized.

Magnetism Reveals a Double Cycle

Hale, studying his sun-spots, confirmed his early impression that the Zeeman effect is exhibited in the solar cyclones. The spots are, then, centers of magnetic influence. Presently it was found that the spots exist in pairs, one representing the positive and the other the negative pole of a magnet—such pairs usually being located at greater or less intervals, side by side, parallel to the sun's equator.

In 1925, Hale and Nicholson announced the discovery that the sun's spots of a new eleven-and-a-half year cycle, which appear in high latitudes after a minimum of solar activity, are of opposite polarities in the northern and southern hemispheres.

"As the cycle progresses the mean latitude of the spots in each hemisphere steadily decreases, but their polarity remains unchanged. The high-latitude spots of the next 11.5-year cycle, which begin to develop more than a year before the last low-latitude spots of the preceding cycle have ceased to appear, are of opposite magnetic polarity."

This law of reversed polarity in successive cycles was found to hold in all but 41 cases out of a total of 1735 bipolar groups. It was therefore concluded that the full spot period, at least that referring to magnetic polarity, is 23 years and not half that time, as the study of spot frequency had seemed to prove.

Professor Turner of Oxford, from a different standpoint, has also found evidence for a difference between successive periods of spot frequency, pointing to the double period.

"We may therefore ultimately find," says Professor Fath,

"that the true spot period, as to both magnetic polarity and frequency, has a mean duration of 23 years."

The observed magnetic condition of the sun's spots makes it seem less anomalous that so-called magnetic storms, associated with violent deflections of the compass-needle, may occur on the earth during periods of sun-spot activity. The terrestrial phenomena, which include the induction of strong electric currents in telegraph and telephone wires, may be explained tentatively as due to the bombardment of the atmosphere by electrons driven out from the sun on sunbeams.

Electronic bombardment of the atmosphere may perhaps also explain the interesting phenomena of the aurora borealis.

Meantime the new studies of sun spots, much as they reveal, leave the causation of the spots themselves as much a mystery as ever. Why they appear seldom more than 40 degrees from the equator, and chiefly in the belts on either side of the equator between 10 and 30 degrees of latitude, is quite unknown. And as to why they show the curious periodicity which the Dessau apothecary discovered so long ago, there has never been even a plausible hypothesis.

The General Surface of the Sun

Leaving the spots with their curious vortex motion out of consideration, the remainder of the sun's surface, as recorded by the spectroheliograph rather curiously suggests an airplane picture of the top of a uniform layer of clouds.

In reality, the resemblance is something more than accidental. The instrument, because it receives the thin film of light of a particular wave-length, takes cognizance of the presence of only a single elementary substance in a given sweep across the surface of the sun.

In one view, for example, it shows the layer of hydrogen, which lies far out in the chromosphere, at the surface of the sun.

Another picture may go a little deeper and show a helium surface.

Yet another reveals a cloud-like stratum of calcium, even higher in the sun's atmosphere than hydrogen.

The presence of the calcium in a gaseous or supergaseous condition at this high level, is a surprise. It can be explained only

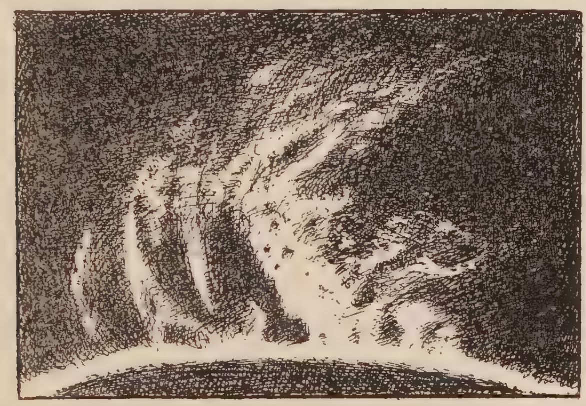

FIG. 85.—A Solar Prominence 150,000 Miles High. (Crow-quilled from photo taken at Mt. Wilson Observatory.)

on the assumption that the calcium atoms, under solar conditions, are partially disrupted, and are swept out into space by the radiation pressure which rushes out in all directions from the great central furnace.

It is estimated by Professor Eddington that the temperature of the surface of the sun is about 6000 degrees Centigrade; and that the temperature rises as the solar depths are reached, to something like 40,000,000 degrees Centigrade at the center. Such figures are little more than words, so far as clear comprehension

of such unworldly conditions is concerned; but they serve at least to give us the impression of an amazing cauldron which is as much hotter than a ball of white hot iron as such a ball is hotter than a cake of ice.

The Sun's Energy and New Atomic Theory

We are all familiar with heat as a mode of molecular motion; but the degree of heat here predicated must be due not to the mere jostling of molecules and atoms of matter against one another, but to the actual disruption of the atoms themselves.

In the modern view, the atom, as originally conceived by Sir Ernest Rutherford, and more elaborately envisaged by Niels Bohr, is a miniature planetary structure, with a central mass of protons (in part mated with the electrons, except in the case of the hydrogen atom) and outlying planetary electrons, revolving at relatively remote distances in orbits which, under normal conditions, are as definitely fixed as the orbits of the sun's planetary families.

The orbital electrons may be driven out of their course through impact with other similar or dissimilar atomic systems—such impact as is involved in the collision between the molecules of a gas.

If the collision be not too severe, the electrons drop back to their normal orbits in due course, and in so doing give out the equivalent of the energy which they received through impact.

The energy thus given out, determined as to precise character by the distance from which the electron falls back to its orbit, or the particular orbit into which it falls, goes out as "radiation energy."

In the older view, this manifested itself as waves in the ether. The newest view does not altogether discard the waves, but is emphatic in declaring that the energy-discharge is not a con-

tinuous stream, but goes forth in what might be thought of as successive arrows or bullets, each of which is called a quantum.

Such is a very crude statement of one essential of the "quantum theory" of Planck, which has taken the modern physical world quite by storm. And such is the Rutherford-Bohr atom, depicted also in only the most general terms, which equally took the world by storm toward the close of the second decade of our century, but which before the close of the third decade had begun to be challenged as to some of its salient characteristics.

For the moment at least, however, the picture of the planetary atom, with almost its entire mass in the central proton-sun, and with its electron-planets, each bearing a unit quantity of negative electricity, remains as a clearly envisaged structure of exceeding convenience for the theorist who would explain the bewildering phenomena (among others) of the sun's internal structure and unbelievable output of energy.

So when we speak of a temperature of 40,000,000 degrees, we must contemplate not merely the interaction of atoms, as such, but the actual disruption of atomic systems.

This conception would have been considered heretical to the point of scientific nihilism in the generation preceding our own. For the conception involves not merely the severing of orbital electrons from their central suns but, in one manner or another, the actual destruction of at least a portion of the veritable substance of the atom—a violation of the sometime "axiom," that matter is indestructible.

In another sense, the matter is not annihilated, but only transformed into energy.

There are two opposite ways, it is conceived, in which this may possibly take place.

Matter and Energy; the Evolution of Atoms

It may be that under conditions of incredible pressure, through which the atomic systems are stripped of their orbital electrons, until protons and electrons become an inchoate mass instead of a collection of orderly mechanisms, there is opportunity (say when the conditions of pressure change as the inchoate matter-stuff boils up toward the surface of the sun) for the coming together, in pairs, of protons and electrons to form hydrogen atoms, and the subsequent coalition of these primordial atoms in groups of four, to form helium atoms.

It is believed that this is the initial process that somewhere, sometime, has taken place in the universe in the building up of matter.

All the more complex forms of matter, of the entire series of ninety-two elements, may be considered as built of helium atoms with residual hydrogen atoms (never more than three of the latter for any given element) to fill in the chinks, as it were, in case the new element is not one that can be made of helium blocks without remainder.

If this does not take place, then the release of an enormous fund of energy is accounted for.

For it is known that the helium atom, though made up of four protons and four electrons, is not precisely four times as heavy as the hydrogen atom, which comprises a single proton and a single electron. That is to say, there has been loss of actual mass—primordial matter—in the construction of a helium atom out of four hydrogen atoms.

There seems no alternative to the belief that this matter has been transformed into energy.

Mathematical calculations give assurance (on the basis of one

of Einstein's formulae) that the amount of energy thus released is colossal.

It is estimated, for example, that the amount of hydrogen in a teaspoonful of water, if thus made to combine to form helium, would release enough energy to drive the largest of ocean liners across the Atlantic.

Here, then, we have a possible source of energy-release that might go far to account for such conditions as appear to obtain in the depths of the sun.

Possible Destruction of Matter in the Sun

According to another view, however, the interior of the sun is the very last place in the world where such combination of protons and electrons, to build up larger atoms, could be expected to take place.

This other view looks rather to the depths of interstellar space as the location where the marriage of protons and electrons, to form helium and perhaps other elements in sequence, is more likely to take place. The "cosmic ray" of Professor Millikan may conceivably represent the flow of energy from such a creative mingling of the primordial elements out in space.

This, obviously, would have nothing to do with the question of temperatures at the heart of the sun.

There remains, however, the alternative thesis, according to which the disrupted atoms, already predicated at the heart of the sun, make possible, not indeed the creative marriage of protons and electrons, but the dashing together of these elements to their mutual destruction.

Such annihilative unions would, it may be supposed, take place in the very depths, at the region of greatest pressure and most intolerable crowding.

It is estimated that the crowding together of protons, stripped

of their outlying electronic orbits, may be so great, under conditions of pressure at the center of some stars, that a cubic inch of the primordial matter there may have the mass—scientific equivalent for weight—of a ton of matter as we know it at the earth's surface.

Under these conditions, it does not seem to strain the probabilities—holding to the modern view of the interchangeability of matter and energy—to suppose that coalition between proton and proton or between electron and proton may result in the actual dissipation of these primordial substances.

And if this takes place, the output of energy would be not merely of the order of that which attends the building of a helium atom, but many times greater, because the entire bulk, and not merely a small fraction of the proton is transformed into energy.

In the view of such mathematical astronomers as Professor Eddington (original sponsor of the theory, in 1924) and Sir James Jeans, such a transformation of matter into energy is incessantly taking place within the structure of the sun and the other suns that make up the stellar universe.

These daring theorists speak as freely of the reduction of the mass of the sun through such transformations as if they were dealing with a structure that could be weighed from hour to hour and its loss of mass evaluated on the scales.

Jeans estimates even, in specific terms, by how much the sun is being reduced in mass day by day, and tells us no less specifically the distance by which the earth's remoteness from the sun must be increased under mandate of the law of gravitation, in compensation.

"The sun's weight," he tells us picturesquely, "has been reduced by a thousand million tons in the last four minutes, with the result that its gravitational grip on the earth has been weakened and the earth has moved out to a wider orbit; at this moment the radius of the earth's orbit is greater than it was four minutes ago. The details can be traced out mathematically with complete precision. It appears that the earth's orbit around the sun is not a circle, or even an ellipse of small eccentricity; it is a spiral curve, like an uncoiled watch spring. Every year the earth moves a tiny step farther out into the outer cold and darkness; exact calculations show that its average distance from the sun increases at the rate of about a meter (39.37 inches) a century."

Is the Sun Losing Weight?

An alluring picture. One almost forgets that it is a purely imaginary picture. No one *knows,* of a certainty that the sun is losing mass. No one *knows* that a single atom of matter has even been transformed into energy since time began.

I say this quite without prejudice, for I have myself been fully convinced of the *probable* transmutability of matter and energy for at least forty years (following my old teacher, Gustav Heinrichs). But here I speak of *proof*. Let that pass for the moment, however.

Riding Sunbeams

Meantime Eddington gives us an inkling of the radiation-power of the energy released by such (imagined) transformation of matter, in the picture he gives of what takes place in the sun's chromosphere.

This outer layer of the sun's atmosphere consists, he says, of a few selective elements which are able to float—not on the top of the sun's atmosphere, but on the *sunbeams*.

"The art of riding a sunbeam is evidently rather difficult, because only a few of the elements have the necessary skill. The

most expert is calcium. The light and nimble hydrogen atom is fairly good at it, but the ponderous calcium atom does it best."

Eddington goes on to explain that the layer of calcium suspended on the sunlight is at least five thousand miles thick.

The skill of the calcium atom in thus riding sunbeams is explained as due to its capacity to lose an electron under impact of the escaping energy, and then to seize it back again.

It must be able "to toss up an electron twenty thousand times a second without ever making the fatal blunder of dropping it. That is not easy even for an atom. Calcium (as it occurs in the chromosphere) scores because it possesses a possible orbit of excitation only a little way above the normal orbit, so that it can juggle the electrons between these two orbits without serious risk. The average time occupied by each performance is one 20,000th of a second."

That does not seem a long time, yet it is divided into two periods, according to theory.

During one period the atom is patiently waiting for a light wave to run into it and throw out the electron.

During the second period the electron revolves steadily in the higher orbit before deciding to come down again. Professor Milne is credited with calculating the relative lengths of these two periods. "Milne's result is," says Professor Eddington, "that an electron tossed into the higher orbits remains there for an average time of a hundred-millionth of a second before it spontaneously drops back again. I may add that during this brief time it makes something like a billion revolutions on the upper orbit."

Which may seem difficult—but not for an electron.

Such, then, are the conditions believed to obtain in that flat

flocculent cloud of calcium which the spectroheliograph reveals and depicts on the photographic plate, as making up a chief constituent of the sun's outermost atmosphere.

Of course the energy which thus plays with calcium atoms, as a hurricane plays with autumn leaves (with the difference that the atoms manage to retain their equilibrium, or to settle back into eddies and thus are not blown altogether away) passes on into space in every direction.

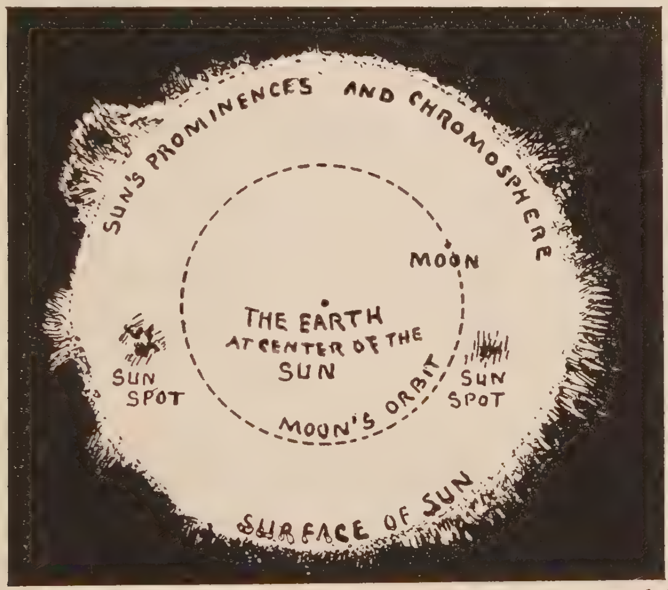

FIG. 86.—A Self-explanatory Diagram of Earth, Moon, and Sun.

The infinitesimal modicum of it that is intercepted by the earth constitutes the heat and light without which there would be no life on our planet.

Old and New Concepts of the Sun's Heat

Such is the newest answer to the problem of the sun's heat, which remote generations did not so much as propound, since to them it seemed natural enough that any observed phenomenon

might go on forever; but which puzzled sorely our predecessors of the latter part of the 19th century.

The doctrine of Helmholtz, exposited by Kelvin, that the sun's heat is due (solely) to contraction, is as obsolete as the older conception that it is merely a ball of fire, being consumed like so much coal.

The newer doctrine that the sun's energy may be due to the presence of radio-active elements was, perhaps, the parent of the doctrine of transmutation from matter to energy, just outlined, though the parent thesis is so far outstripped as to seem almost old-fashioned, notwithstanding its recent origin.

Yet, basically, the new theories are evolutionary rather than revolutionary.

Even in the later day of the 19th century, when the conventional view of science was that matter is one thing, energy another, each fundamental, each indestructible, there were forward-looking students who conceived a monistic universe, with ultimate unity back of the seeming diversity everywhere in nature.

For such, the ultimate transmutability of the elements seemed the most plausible of theses. To them matter and energy seemed but different aspects of the same entity.

For these holders of what then seemed visionary views (I am glad to count myself among them), the developments of the first generation of the 20th century were rather of the order of the happening of the expected, than the revolutionary changes that they appear from a more conservative standpoint.

But if we go a little further back in time, and reflect, for example, that the elder Herschel, at the beginning of the 19th century, exposited the view that the sun is a habitable structure,

with pleasant regions suitable for human occupation beneath the outer canopy of glowing ether, the contrast between that view and the new conception of the sun—with six-thousand-degrees surface and forty-million-degrees center—seems indeed revolutionary.

The Old Idea of an Inhabited Sun

To understand the transformation, we have only to reflect that in Herschel's day man was still considered the supreme Creation of the universe.

The earth had indeed been dethroned from its central place in our system, but it was conceived that an infinitude of other worlds had populations closely akin to our own race. That all the universes of new worlds revealed by the telescopes of Herschel had been designed by a beneficent Creator as the abiding-place of races closely comparable to our own, was the natural view of the heritors of the egocentric and anthropomorphic tradition.

The real import of the Copernican revolution was for the most part not even suspected.

A century's advance of astronomical science has made it certain that there are no human-like inhabitants of the sun, nor of any other star. Probably none on sister planets of our system—with the conceivable exception of Mars and Venus. The habitability of these two planets is more than doubtful: the weight of evidence is all on the other side. And there is growing doubt in the minds of astronomers as to whether the universe contains a great number of planetary systems similar to ours, in which conditions suitable for anything like life as we know it obtain.

A few billion such there may be, but by and large, according

to the popular present-day guess, the stellar systems are uninhabited.

So greatly has the viewpoint changed, however, that no one whose sense of humor permits him properly to appraise the relation of the human race to the newly revealed universe of perhaps 100,000 million stars, can feel that the question has any conceivable importance.

A sane appraisal would seem to reveal mankind as merely the agent of a minor microbic disease on the surface of a planet of totally negligible significance. Whether a few million or billion other planets suffer from a like malady may from man's standpoint have an element of "human interest" but can have no bearing on larger questions of the origin and destiny of the universe.

To have had a large share in bringing man to this plane of comprehension, out of the age-long dream of egocentric anthropomorphism, is doubtless the most useful achievement of astronomical science.

XXX

LANGLEY—HERTZSPRUNG—RUSSELL—NEW LIGHT ON THE STARS

It requires no instrumental aid to prove that the sun sends us light and heat. But very little was known about the precise quantities of energy involved and in particular about

the variations in quantity from hour to hour and from day to day, until Professor S. P. Langley invented the instrument called the bolometer.

Langley is known to the astronomical world for his pioneer work in charting the sun's rays with this instrument. His popular fame was chiefly gained by his experiments in the attempt to develop a heavier-than-air machine that would fly.

In the day when the air as yet was unconquered, Langley made a model that did fly, and he came bitterly near success with his man-carrying "aerodrome," which dropped into the Potomac only a few days before the Wright Brothers achieved success and immortal fame down at Kittihawk.

It will be recalled, perhaps, that the Langley machine was subsequently taken from its repose in the Smithsonian Institution and made to fly—but only with the addition of the equivalent of the warping wings which the Wright brothers had developed and without which no aeroplane takes the air even to this day. But Langley was as near success as anyone was destined to come before the two young men solved the riddle, and his ultimate failure, when the goal seemed so near, was a bitter experience.

In that day, the philosophy that imbues the mind of the star-gazer must have been a solace. And fortunately for himself Langley was endowed with an abiding sense of humor and an imagination that would enable him to evaluate the significance of his failure—and thereby to make the disappointment endurable.

Langley's Bolometer Described by Dr. Abbot

The bolometer with which Langley made his extraordinary measurements of the sun's varying output of energy, is described by Dr. C. G. Abbot, who has followed up the work no less

searchingly, as an electrical thermometer, with two hair-like ribbons of platinum, as long as one's finger nail, blackened with lamp-black, one of them fitting behind a metal plate.

"As the rays of the solar spectrum fall upon the exposed one, it warms it above the temperature of its hidden neighbor. The

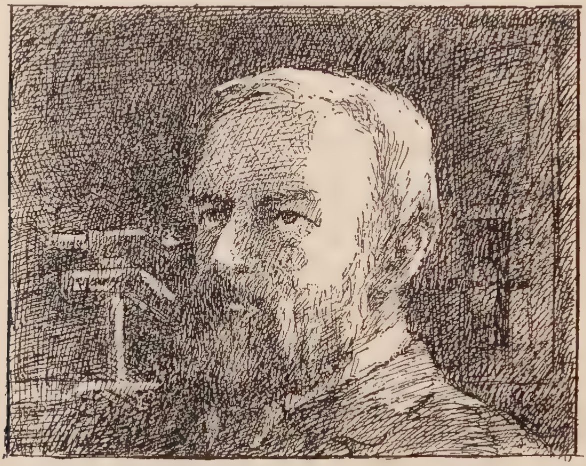

FIG. 87.—Samuel P. Langley (1834-1906). (Crow-quilled from photo by Brown Brothers.)

tiny temperature difference, even if less than 1/1,000,000 degree, suffices to alter the electric current balance of which the two ribbons form parts, and a little mirror, smaller than a pinhead, is turned by the electromagnetic impulse which the current-change produces.

"A tiny shift of sunlight reflected by the mirror moves across a photographic plate, and so records the warming or cooling of the exposed ribbon of the bolometer."

There is a clockwork mechanism and a photographic plate, and the solar spectrum is moved back and forth across the sen-

sitive wires, making a permanent record of what Langley called "solar-energy spectrum curve" or "bolograph."

This record showed not only the energy of the spectrum itself, but also recorded heat far beyond the ends of the spectrum visible to the eye.

The method thus measures the total energy of the solar radiation, not merely that associated with the visible rays.

The same apparatus, and a somewhat similar one called a radiometer, has been used to test also the energy of the stars.

The Energy and Substance of Stars

So sensitive was an instrument used by Nichols and Hull, that it had power to evaluate an amount of energy equivalent to that which would be received from a candle twenty miles distant.

It could perform the necromantic task of registering and measuring the heat from larger stars and planets. Radiant heat is, after all, only a longer-wave form of light, but we are so accustomed to think of star-light as "cold" that the idea of its inherent warmth seems anomalous.

High interest attaches to such energy-tests as these, but of course the chief star-records, upon which our knowledge of the sidereal universe depends, are exclusively light-records. In recent years, however, various highly ingenious methods have been devised for interpreting the light-messages in terms of the structure of the almost infinitely distant light-emitting stellar body.

To begin with, of course the spectroscopic record tells much, when it has revealed the chemical composition of a star, even in part.

In our nearby star, the sun, for example, no fewer than sixty-six of the terrestrial elements have been located.

The rays of the stars proper, enfeebled by distance, do not give so comprehensive a record.

Yet there are thousands of stars in which nearly as familiar elements are unequivocally revealed as if the tests were being made in a laboratory. On the other hand, with perhaps a single exception, there is no spectroscopic record of any solar or stellar element that is not known here on the earth.

In general, the chemistry of the stars is familiar terrestrial chemistry.

Star Spectrums

It will be recalled that helium was discovered in the sun (and indeed so named because of its location there) long before it was known as a terrestrial element—though now we know that it is present everywhere in the atmosphere in minute quantities, and is a relatively abundant exudate in certain oil wells; and, indeed, a universal by-product of radio-active elements everywhere in the soil.

In some stars, the spectrum of helium is so conspicuous that the name "helium stars" seems appropriate.

Other stars are known as "hydrogen stars" because their outer atmosphere, possibly also their deeper structure, is aglow with that element.

Iron is widely distributed in others, and the less familiar element titanium is more conspicuous than might be expected—though the general lack of familiarity with this element is due not to its scarcity in the earth's crust, but to the fact that hitherto no conspicuous commercial use has been found for it.

We have seen, in the preceding chapter, that the modern view takes cognizance of the probability that the more complex elements are dissociated under the conditions of heat and pressure that obtain in the sun.

Since the stars are only distant suns, vast numbers of them

enormously larger than our own luminary, it goes without saying that similar conditions must obtain in their depths.

It is easily conceivable that "hydrogen stars" may consist almost or quite exclusively of the element hydrogen alone, since that is the most primitive of all elements—the basic structure out of which the more complex elements are believed to be built.

Star Substance

In any event, it is known that many of the largest and most brilliant stars are of excessively tenuous structure—some of them composed of gas of such extreme rarefaction that it is the equivalent of what in the terrestrial laboratory is called a high vacuum.

This seems almost incredible, since we are accustomed to think of stars as solid bodies.

But the conclusion is unescapable, when the observed bulk of the star is considered in connection with its mass, as demonstrated by a neighboring star with which it constitutes a binary system.

The bulk of a star, it should be explained, is not determined by actual measurement (except in the few recent cases where the magic interferometer of Professor Michelson has been applied), but is inferred from the star's brightness in connection with the parallax, or more usually lack of parallax, that demonstrates its extreme distance.

It may be added that the stars which have yielded directly to measurement with the interferometer—Betelgeuse, Aldebaran—show diameters closely corresponding to the estimates that had previously been made by the light-gauging method.

The fact that the stars vary in color from blue or white to orange or red early led to suggestions for their classification on this basis. In this work Father Secchi, at Rome, was the pioneer. But as he depended upon visual observation, he necessarily only

prepared the way for the more elaborate investigations that were subsequently to be made with the spectroscope.

At Harvard Observatory, under the directorship of E. C. Pickering, this work was developed (along lines detailed in an earlier chapter) on the basis of roughly a quarter of a million stellar structures, photographed with an objective prism instrument. The results of this work, collated notably by Miss Cannon, have been published in nine large volumes, dedicated as a memorial to Dr. Henry Draper, a great pioneer in stellar spectroscopy.

The Draper Classification

According to this so-called Draper Classification, the principal classes of stars are denoted in the following order, by the letters O, B, A, F, G, K, M, R, N and S.

Ninety percent of the stars are included within the six classes B to M. Each type of star has sub-divisions, numbered from 1 to 9, except type M, the sub-divisions of which are lettered.

Class B stars show prominently the lines of hydrogen and helium. In some of these stars, the helium is partially disrupted; such also is the state of silicon, oxygen, and nitrogen. Stars of this class are sometimes called "helium stars" or "Orion stars." Prominent representatives are Rigel, Regulus, the bright stars in the Pleiades, and several stars in the constellation of Orion.

The stars of the remaining prominent classes are characterized as follows by Dr. W. M. Smart:

"Class A. In spectra of this type, the lines of hydrogen are the most prominent. The lines of several metals, notably those of ionised calcium and magnesium, are in evidence, but weak in comparison with the conspicuous lines of hydrogen. Sirius Vega, and Castor are stars belonging to this class.

"Class F. In spectra of this class, the hydrogen lines become less prominent and the lines of metals—notably the H and K

lines of ionized calcium—gain in importance. Near the end of this class, at F8 and F9, the spectra bears a strong resemblance to the solar spectrum. Typical F stars are Procyon and Canopus, which are white stars.

"Class G. This is the class to which the sun belongs. The spectrum is remarkable for the enormous number of metallic lines—notably the lines of neutral, that is, un-ionised iron; the lines of hydrogen and ionized calcium are still prominent. Typical stars are the sun and Capella,—both of type G; these stars are yellow in colour.

"Class K. Bright stars in this class are Arcturus and Aldebaran. The lines of ionized metals become weaker; the lines of neutral metals become stronger. Near the end of this class there is evidence of the bands of titanium oxide. The stars of this group are orange in colour.

"Class M. The important feature of stars of Class M is the great strength of the bands of titanium oxide; the lines of neutral metals are also prominent. The stars in this class are red; Antares and Betelgeuse belong to Class M.

"The spectra of the sequence B to M, are, with a few exceptions, absorption spectra—that is, each spectrum consists of the rainbow colors, red, orange, etc., to violet, crossed by dark lines. In Class O the most important lines are *bright* lines of hydrogen, of ionized helium, carbon, oxygen and nitrogen; there are, in addition, several bright lines of unknown origin. The classes R, N and S may be regarded in some respects as sub-divisions of Secchi's Class IV—they are red stars and comparatively rare in the heavens."

It will be noted that there is here a gradation from blue stars to red.

The Star-Scale Interpreted

It is justifiably inferred that the colors evidence variations in temperature, comparable to those shown by a heated iron which becomes first red hot and then white hot.

Elaborate analyses of the spectroscopic records of these stars, supplemented by Dr. Abbot's tests with the bolometer, have led to interpretations of technical character—"Wien's law," "Stephan's law," "Planck curves"—of the typical temperatures of the various types of stars under consideration, according to which stars of the white or blue type exhibit a surface temperature of upward of 35,000 degrees centigrade, while stars of the M or red type may have as low a temperature as 3,000 degrees—comparable to the temperature of molten iron.

Well may it be spoken of as "indeed a marvelous achievement that the temperature of stars, tens and hundreds of light years away from us, can be measured with such remarkable precision."

Here, it is observed, the astronomer comes to the aid of his confrère, the physicist, since in the hottest stars, matter exists under conditions unapproached in the laboratory, and the study of stellar spectra leads to a more intimate knowledge of the structure and behavior of the atom than could be attained from merely terrestrial observation.

It is these studies, chiefly, that have made the conception of the partly dissociated atom—the nucleus wholly or partly stripped of its electrons—familiar.

In the myriads of sidereal laboratories open to our observation, through the medium of the necromantic spectroscope and telescope, we witness transmutations of elements comparable to those which the mediaeval alchemists perennially dreamed of, and which the 19th century chemistry mistakenly pronounced an inconceivability.

One would search long for a stranger dénouement than that of the efforts of the searchers who turned their eyes upward to the far places of the heavens.

Star Motions and Origins

There remains an exceedingly curious additional fact to be noted in connection with the stars of the Draper classification. It is found that, by and large, the hot stars are moving with relative slowness and the red stars with greatly increased speed, there being an even gradation throughout the intermediate ranks.

Thus the average for B stars, according to Dr. Plaskett, is 6.5 kilometers per second; that for class A stars 10.9 kilometers, and so on, up the scale to a speed of 17.1 kilometers per second for the cool, or red, stars of Class M.

There is ample food for reflection in this record of disparity of speed between stars of different types. The thought naturally suggests itself that, conceivably, the hotter, more gaseous, star may be younger, and therefore has not yet acquired the momentum which the cooler stars have attained through falling for a longer period towards some imaginable center of gravity represented by the center of the universe itself or by some aggregation of matter which has dominating influence.

There is at least a certain measure of plausibility in such a suggestion.

But have we any evidence that the blue stars are indeed younger than the red ones?

In examining that question, we are brought face to face with the question of the origin of the stars and their life-history.

There is no other astronomical question, perhaps no question in any other field of science, that has greater interest than this. Let us make inquiry as to the way in which contemporary astronomers have endeavored to answer it.

In so doing we shall find ourselves at the very frontiers of 20th century astronomy.

As we pass from the theme of cosmology to that of cosmogony, we shall witness the effort to read the story of Creation, the story of the birth of heavenly bodies, the story of the evolution of world-systems, with the scroll of the firmament itself for our text.

Which after all is only putting ourselves in the attitude of our remote ancestors of prehistoric times, and of their descendants of the early civilizations, who perennially scrutinized the heavens, and whose interpretations were recorded by the scribes at the very dawn of history, to become traditions, sacred with age, which we of this latter day are only now beginning to challenge effectively, and supplant.

But there is this significant difference, that we of the new generation have instrumental aid in searching out the meaning of the sidereal scroll, which our forebears were denied. Perhaps we may hope, then, that the new interpretation will be an advance upon the old one. Let us in any event inspect it.

The Life-History of a Star

The basic classification of stars, everywhere accepted in the early part of our century, is the "Draper Classification" above outlined.

As originally interpreted, the series represents consecutive stages of star-development—presumably from a hot stage through successive stages of cooling, to be followed by extinction.

But about the year 1913, two men, Professor E. Hertzsprung, of Leyden, and Professor H. N. Russell, of Princeton University, independently made observations that tended to render this interpretation debatable.

They observed that stars of the M (cool) type of the Draper

Plate XX: The 24-inch Bruce Reflector of Harvard College Observatory at Arequipa, Peru

classification are of two quite different orders of magnitude—one group enormously large, the other group amazingly small, as stars go.

The two groups came to be dubbed, respectively, Giants and Dwarfs—these "happily descriptive terms" being chosen by Hertzsprung.

It was Russell who followed up the discovery in the year 1913 by collecting data for all the known members of the two groups, between two and three hundred, whose distances were then approximately known. He calculated their absolute magnitude—that is to say, the magnitude each star would have if fixed at such a distance from the earth that the parallax would be one-tenth of a second.

Dividing the stars into their spectrum classes, he produced an extraordinary diagram which showed, among other things, that in Classes B and A (hot, white or blue stars) there are no *faint* stars; and in Classes K and M (cool, red or iron stars) there are no stars of *medium* brightness; all are either very bright or very faint.

A veritable bombshell this—a stick of dynamite cast into the world of astronomical speculation. For it had come to be taken for granted that stars of one Draper class are stars of one age. Young stars, large and white-hot; old stars, small and only red-hot, which is the equivalent of cool, as things go in the sidereal world.

Giants and Dwarfs

And now it appeared that a cool red star could be either a giant or a dwarf—at once young and old, according to the standard interpretation.

It was altogether disconcerting.

But Professor Russell's observations were fortified by an unex-

pected wealth of new material, resulting from the discovery of a method of testing star parallaxes with the spectroscope, as applied by Dr. W. S. Adams, of the Mt. Wilson Observatory.

Now there could be no question that the red stars are divisible into two groups of totally different magnitude.

One group of the red stars (M) was found to be ten magnitudes, or ten thousand times, brighter than the other group.

The average giant appeared to have a million times the volume of the average dwarf.

And there were no intermediate red stars between the giants and the dwarfs. That, indeed, was the strangest part of the story.

The interpretation of the anomaly, as given by Professor Russell, was that red giants and red dwarfs represent the youth-stage and senility-stage respectively of a star, and that the intermediate stages of the star's life-history are represented by the other coteries—B, A, F, G and K of the Draper classification with their various subdivisions—which had hitherto been supposed to belong to independent categories.

Advance and Decline of a Star

The life-story of a star, according to this new interpretation, begins with a vast, relatively cool nebulous stage represented by the giant M; evolves through class G and the other intermediate stages to a culmination in the white or blue star stage of class B, or perhaps O; after which there is the decline of advancing age, with decreasing size, progressive cooling; a second childhood in a class G stage (our sun is here); and ultimate senility in the cool-dwarf of the final class M.

This is such a progress of evolution and devolution as Lockyer had conceived and clearly outlined a good many years before.

But since most astronomers had paid no attention whatsoever

to Lockyer's speculations, or had put them aside as utterly visionary, the new estimate of the life-history of a star, fortified now by a wealth of concrete observations, came as a bewildering surprise.

Fig. 88.—Dr. Pease Measuring a Star with Interferometer and 100-inch Reflector at Mt. Wilson. (Crow-quilled from Brown Brothers' photograph.)

Needless to say the new speculations were not universally accepted. But in the ensuing years additional evidence in their support was found in the results of investigations of independent character.

The Direct Measurement of a Star

There is, for example, the altogether amazing feat—the most spectacular astronomical achievement of the century—of measuring directly the diameter of a star.

This was accomplished at Mt. Wilson, with the great reflector, equipped with the extraordinary instrument called an Interferometer, the creation of Professor A. A. Michelson, of the University of Chicago.

The actual measurements were made largely by Dr. Pease.

The instrument consists of a long beam of structural steel, placed across the upper end of the tube of the one-hundred-inch telescope. This beam carries near either end a small mirror, and the two mirrors can be adjusted by sliding back and forth, until their reflected beams from the image of a star are brought together in such wise as to produce alternate bright and dark bands, or "fringes."

With a certain separation of the two light-collectors, the fringes almost disappear.

Here the position of the two mirrors is measured, and by a calculation which, from the standpoint of the mathematician, is not unduly intricate (but which no non-mathematical mind could be expected to understand), the diameter of the star from which the light-beams came, is determined.

As a matter of course the stars first selected for measurement were certain ones accredited to be of gigantic size—brilliant, not because of their relative nearness (as in the case of Sirius), but because of their actual magnitude.

The first of all was the famous Betelgeuse, known from antiquity as the famous red star of first magnitude in the shoulder of Orion, and bearing in recent times a name which it received from the Arabian astronomers.

This big red star (a dullish red to naked-eye view) was accredited one of the largest of the company of class M giants.

The interferometer measurement, made on a night of December, 1920, brilliantly confirmed the estimate of the enormous size of Betelgeuse. The measurement of the star was an almost unbelievable achievement (recall that even this giant appears only as a point of light in the field of the most powerful telescope).

The implication of the measurement—showing that the theoretical estimates of star dimensions were dependable—was, from the standpoint of cosmogonic speculation, tremendously significant.

Giants That *Are* Giants

Mere words and figures give no conception as to the magnitude of this class M giant. To say that Betelgeuse is 250,000,000 miles in diameter is to use meaningless words.

To say that it is 300 times the diameter of the sun perhaps makes the picture a trifle more concrete.

Best of all, perhaps, is the estimate which shows that if Betelgeuse were placed in the position of our sun, its surface would extend far out to the neighborhood of the orbit of Mars, leaving the earth encompassed within the substance of the great M star itself, at a depth of more than 30,000,000 miles.

Appropriate indeed for such a colossus—yet after all how inadequate—is the name Giant.

Other measurements followed. Mira Ceti proved even larger than Betelgeuse—big enough to extend far beyond the orbit of Mars were it in the position of our sun.

Aldebaran, a yellow star, proved of intermediate size. The brilliant white star Sirius, and Vega, both of class A, are enormously large in comparison with the sun, to be sure, yet pigmies beside the class M giants. Indeed, Vega, much the larger of the two,

appears as only a dot, like a period on the printed page, on a diagram that shows Mira something like two inches in diameter.

On this same scale, it may be added, Arcturus appears about the size of a capital O on this page, though in the sky, to visual observation, this orange star shines at first magnitude.

The Testimony of Eclipsing Binaries

Only the largest stars can as yet be measured with the interferometer, but the results of these measurements strongly support the validity of estimates made by other methods. And stars of other types form series strongly supporting the Russell theory.

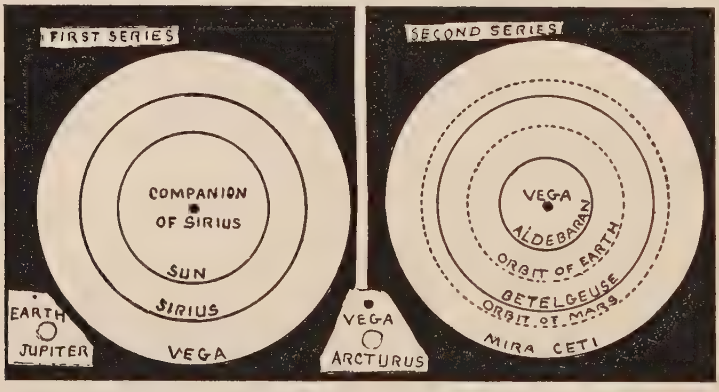

FIG. 89.—Comparative Sizes Among Stars.

There are certain so-called eclipsing binaries of class B, for example, whose diameters vary from about three to eight times the diameter of the sun.

This is quite in accordance with theory—since class B stars are intermediate in age between the red giants and the sun.

Also there is at least one binary of type M that has been under observation.

Estimating the sizes of the components of this revolving system by the usual gravitational methods, it is found that the components of the system are but little more than half the solar diam-

eter. In volume as well as in luminosity they are but insignificant dwarfs.

Their density is about four times that of water—indicating that their structure is of the order of composition of the earth, and vastly more dense than the average substance of the sun.

All this carries out the conception that the giant red stars are in the stage of babyhood, and that the red dwarf stars are nearing the end of their period of luminosity.

A Disconcerting White Dwarf

So convincing is the evidence that it can be said that as recently as 1924, the giant-and-dwarf thesis of stellar life-history seemed by way of general acceptance among astronomers as the valid interpretation of the evolutionary history of stars in general.

Nor has the theory by any manner of means been altogether superseded in the ensuing years.

But it is held by many astronomers that serious doubt has been cast upon its validity by new discoveries of another order—the discovery, or interpretation, of the relation between stellar mass and luminosity.

This discovery or interpretation is associated with the observation of stars that are called *White* dwarfs—a type of star not accounted for in the Draper classification, and therefore requiring consideration from another viewpoint.

The most famous example of the white dwarf clan (of which only three members all told are known) is the companion of the bright star Sirius, which was discovered by the American telescope maker, Alvan G. Clark, after its existence had been predicated theoretically by the great Bessel because of observed irregularities in the motion of Sirius itself.

The orbit in which Sirius and its small companion revolve is accurately known, and the masses of the two stars. Sirius itself

has about two and one-half times the mass of our sun, whereas the "white dwarf" companion is smaller than the sun by about one-sixth. Not precisely a midget, therefore, but a true dwarf, according to sidereal standards.

As viewed from the earth, the companion is described as ten magnitudes smaller than Sirius. Otherwise stated, Sirius is ten thousand times brighter than its companion.

Odd Characteristics of the White Dwarf

The comparison with the sun, as just made, is misleading.

For whereas the mass of the white dwarf is not so far below that of the sun, by the tape line the star is a veritable dwarf, having a diameter of only twenty-four thousand miles—three times the diameter of the earth.

Uranus, the planet next in size above the earth, has a diameter of thirty-two thousand miles. Jupiter, of course, is far larger still.

Thus the companion of Sirius is seen to be a body of ordinary planetary size—yet it is a self-luminous star, shining like any other star because of its own inherent hotness; and shining, indeed, with the spectrum of the F group of the Draper classification, which is just below class A, to which Sirius itself belongs.

The significance of all this may be summarized in the statement that the density of this white dwarf companion of Sirius is computed to be fifty thousand times that of water.

As Dr. Smart remarks, one ton of the material of this star could be stowed away comfortably in a matchbox.

Osmium, the most dense substance known here on the earth, has about twenty-two and one-half times the density of water—as against the fifty thousand of the white dwarf.

It seemed impossible to credit the calculations that ascribed such properties to this star—because ordinary dwarf stars are *not*

white hot, but on the contrary are cool to redness. A way must be found to test the calculation that ascribed such anomalous qualities to the white dwarf.

Enter now the mathematician, Albert Einstein. Not in person, to be sure, but as represented by his world-famed theory of relativity.

The Acid Test

The man who applied the theory, in this instance, was Dr. Adams at Mt. Wilson Observatory. The apparatus with which he worked was a spectroscope. What he did, specifically, was to test the lines in the spectrum of the companion, and to determine that they are shifted far more toward the red end of the spectrum than could be expected except under one condition.

This condition is that the light sent out from the surface of the white companion comes from matter of excessive density.

One of the three practical tests suggested for the validity of the Einstein theory is that light from the sun should show its lines shifted very slightly toward the red end of the spectrum, and that light from a more dense body should show them correspondingly farther shifted.

According to theory, if the Companion of Sirius is really as dense as had been estimated, the shift of the lines (technically expressed in terms of kilometers per second, because under other conditions a similar shift represents the speed of a star in the line of sight) should be 20.

Dr. Adams, after making all allowances for motions of the Companion, deduced the value 19.

Obviously, here was something approaching a demonstration. Professor Eddington says of this test:

What the Test Seems to Prove

"Professor Adams has thus killed two birds with one stone. He has carried out a new test of Einstein's general theory of

relativity, and he has shown that matter at least two thousand times denser than platinum is not only possible, but actually exists in the stellar universe."

Now for the complication. If the Companion were a cool red star, of low luminosity, it would fall into the scheme of stellar evolution as a dwarf of M type, therefore at the last stage of devolution. But as the case stands, the Companion is a brilliantly luminous white star, having the effect of a gaseous structure instead of a liquid or solid, yet being enormously more dense than any terrestrial liquid or solid.

The accepted thesis of the Russell scheme of stellar growth and decay had been that the turning-point in the history of a star at the white stage, came at the stage when a degree of cooling was attained at which the star ceased to be gaseous.

After that, it was supposed to be a matter of continued cooling and contraction, with loss of actual substance, as descent was made to the stage of solid matters, still glowing like red-hot iron, but at a surface temperature not greater than may be achieved in the terrestrial laboratory.

The anomaly of the companion—and the known presence of at least two other white dwarfs in the stellar system, with the probability that many more exist—was held to vitiate the Russell theory, putting it thoroughly under suspicion.

"We no longer admit," says Eddington, "that stellar substance will cease to behave as a perfect gas at one-quarter the density of water. Our result that the material in the dense dwarf stars is still a perfect gas strikes a fatal blow at this part of the giant and dwarf theory."

He adds, however, that though the theory of stellar evolution must be considered as in the melting-pot, he is disposed still to

believe that the former theory was right in assuming that the sequence of evolution is from diffuse to dense stars.

Yet it appears that, at least as to its broad lines, the theory of stellar evolution presented by Russell can still be maintained if it be conceded that within the body of the star there may take place actual annihilation of matter, or other sub-atomic release of energy, such as was referred to in the preceding chapter when the conditions within the sun were under discussion.

But if this is admitted, there seems no reason why a skeptical attitude should be taken toward the thesis of stellar evolution from cool body to hot body and back again to cool; for the leading mathematical astronomers of today, with certain notable exceptions, have come to accept the possibility of such a transformation of matter into energy, not merely as a working hypothesis, but apparently as a theory firmly believed to be in accord with the actualities.

At all events the Russell theory of the life story of a star stands as the most plausible interpretation of the observed differences in stellar constitutions that has hitherto been presented.

XXXI

LEAVITT—SHAPLEY—AITKEN—STARS THAT ARE DIFFERENT

THERE have been singularly few women to attain prominence in the astronomical world. But at least one woman in our own time has made a major discovery in this field. I refer to Miss

Leavitt, and the discovery of the relation between actual brightness and rate of pulsation of the very famous stars known as Cepheid Variables.

The discovery was not made by direct star-gazing. It was made by the more typically modern method of examining photographic negatives in the laboratory.

The negatives under observation were taken at the celebrated Harvard University Observatory at Arequipa, Peru. Their subject was the long-known nebulosity of the southern hemisphere called the lesser Magellanic Cloud—a celestial object invisible from temperate zones of the northern hemisphere, but famed as forming, together with its more conspicuous companion-structure the greater Magellanic Cloud, a unique exhibit in the circumpolar region of the other hemisphere.

These nebulosities were among the phenomena of the southern heavens to which Sir John Herschel gave special attention during his famous sojourn in South Africa.

They have interest, among other things, because they lie far outside the Milky Way as isolated islands of nebulosity, as if two handfuls of the substance of the Milky Way itself had been plucked out and placed near the frontiers of the Galactic system, the two being separated by about sixty degrees of longitude, but having approximately the same latitude, or declination.

Herschel explains that the greater cloud is sufficiently bright to be visible even on a moonlight night, though the lesser one is then blotted out by the moon's radiance. On a moonless night, the lesser cloud is modestly, and the greater one strikingly, conspicuous to naked eye observation, though hardly to be called spectacular. To telescopic observation, both clouds are objects of peculiar interest.

The negative that especially attracted Miss Leavitt's attention was taken with the great reflector designed for photographic rather than direct examination of the heavens.

The Photographic Record

Similar negatives had been many times studied, and very likely this particular negative had passed under many eyes. But it was reserved for this woman observer to note a certain peculiarity of the record which was destined, as subsequently

FIG. 90.—The Greater Magellanic Cloud. (Adapted from photo, credited to the Union Observatory, Johannesburg.)

interpreted, to prove of altogether startling significance. Truly momentous, from the standpoint of the science of sidereal astronomy.

Yet the observation in itself was simple enough—albeit demanding keen eyes and a clearly-coordinating brain.

It consisted in comparison of the numerous stars of a certain type among the multitudes of ordinary stars sprinkling the plate—rounding these up, as it were, and checking them off as regards their varying degrees of brightness.

And noting—this constituted the discovery—a certain puzzling relation between brightness of the stars and the unique particu-

larity according to which the stars in question were grouped together.

This particularity was, and is, that the stars in question—the ones sorted out and listed together, though sprinkled at various places in the Magellanic cluster—are *pulsing* stars.

That is to say, they are stars that seem to expand and contract, with perfect regularity of pulsation, like throbbing hearts,

FIG. 91.—Miss H. Leavitt. (Crow-quilled from an original photograph by Mr. William Henry.) At Miss Leavitt's right is the binocular instrument with which studies were made that led to her discovery of the Period Luminosity Law.

each individual star having its own particular rate of pulsation which never varies—the period of some stars being only a few hours, for others several days, but in no case more than about a month.

Such pulsing stars would be considered perhaps the strangest members of the sidereal family were it not that we ordinarily associate strangeness with rarity, and stars having this peculiarity

can hardly be called rare, as they are scattered here and there in most parts of the heaven. On the other hand in the relative scale, considering that they number only scores, as against the billions of stars that do not pulsate, these Cepheid Variables, that being their name, *are* rarities.

Their strange conduct has, naturally, excited high interest since the time, more than a century ago, when the first member of the clan was observed to manifest its anomalous particularity of action.

Peculiarities of Pulsing Variables

This first of pulsing stars to be observed is faintly visible to the naked eye in the constellation Cepheus.

Hence the name Cepheid Variable, which came to stand as the class name for all stars of this type when, presently, it was observed that the original Delta Cephei was by no means unique, but had numerous imitators in various parts of the sidereal system.

As a rule, the Cepheid Variables are located in the midst of clusters of stars, in particular they frequent the compact globular clusters—a fortunate penchant for the astronomer, as we shall see presently.

But what, then, did Miss Leavitt discover as to the relation between brightness and pulsation-rhythm among the Cepheid Variables of the Magellanic Cloud depicted on the Arequipa negative?

Why simply this: that all the variables of rapid pulsation were *faint* stars—of low visibility. All stars having pulsation-periods of less than one day were exceedingly faint. Stars of progressively slower periods of pulsation were progressively brighter. And the slowest-pulsers of all were the brightest of all.

It should be explained that the pulsation-period—or, to speak

more technically the periods of variation—of all the numerous Cepheids hitherto observed were matters of established record—thanks to the patient observations of the star-gazers of several generations. Miss Leavitt's discovery had nothing to do with that. It was perfectly well known that the numerous Cepheids in the Magellanic Cloud had various periods of pulsation, from very rapid to very slow as things go in the Cepheid-Variable world. The thing that had not been known was that there exists any definable relation between these variant rates of pulsation and the degree of maximum brightness of the different individual members of the clan.

Even now that it was shown that such a relation does exist, nothing much might have been made of it, for off-hand it does not seem a matter of particular moment that certain exceedingly faint telescopic stars billions of miles away fluctuate in brightness at short intervals, whereas certain others slightly less faint stars in the same sidereal neighborhood fluctuate somewhat less slowly.

But there were two astronomers in the world who were at once struck, when they heard of Miss Leavitt's discovery, with the thought that here was something that might prove of far wider significance than at first blush appeared—which might, indeed, give the clue to an altogether new type of investigation of some of the profoundest secrets of the system of stars.

One of these men was Prof. E. Hertzsprung, of Leyden.

The other was Dr. Harlow Shapley, then of Mt. Wilson Observatory, subsequently Professor of Astronomy at Harvard.

To each of them it occurred that Miss Leavitt's discovery that the "period of fluctuation of a Cepheid depends on its candle-power" (as Sir James Jeans phrases it) might be used to test

the *distance* of other Cepheid Variables, wherever situated, even to the remotest parts of the visible universe.

Cepheid Variables as Distance-Gauges

The point is this: the Magellanic Cloud is so exceedingly distant from the earth, that the Cepheid Variables scattered through it (though in reality scattered through an area scores of light-years in extent) may be regarded as practically at the same distance from our planet. Therefore their apparent variations in brightness represent actual or intrinsic variations. The seemingly faint stars are actually of low candle-power; the bright ones of high candle-power.

In a word, a certain rate of pulsation is uniformly associated with a certain degree of intrinsic luminosity.

But special studies had long been made of the apparent brightness of stars; indeed, from ancient times and throughout the generations, relative brightness was the standard according to which stars were listed as of the first magnitude, second magnitude, etc., through the six magnitudes of naked-eye stars and the decreasing magnitudes to the 20th or 21st as revealed by telescopes successively more powerful.

But of course it was familiarly recognized, in modern times, that there is no necessarily close relation between apparent brightness of a star, as we view it, and intrinsic brightness—the matter of distance being an obvious disturbing factor.

The dazzling brilliant Sirius, for example, appears so bright merely because it is relatively near. In the absolute scale it is a star of only moderate luminosity, inferior to multitudes of stars which, because of their distance, are totally invisible to the unaided eye, and appear only as the faintest of specks in the most powerful telescopes.

Astronomers are not altogether without clues for discrimina-

tion between apparent brightness and actual brightness, but there had been no star-gauge available in the least comparable to the one that the new Cepheid discovery seemed to offer. For here were stars which (thanks to Miss Leavitt's discovery) were now seen to signal directly the record of their intrinsic brightness—to signal it by pulsing at a definite rate, just as a light-house beacon signals its identification by its intervals of intermission.

It remained only for the observer to note the *apparent* brightness, as viewed from the earth, of the star whose *actual* brightness was thus signaled in order to compute the relative distance of this star in comparison with the distance of any other Cepheid Variable similarly observed.

Thus one Cepheid Variable could be compared with another as to relative distance throughout the entire group of Cepheids. And if the actual distance of any one Cepheid was known the actual distances of all others could be readily computed.

Thus reasoned the two imaginative astronomers, one in Germany and one in California, on learning of the crude signals that the negative of the Magellanic Cloud had revealed to the Harvard Observatory investigator.

It was the California astronomer, who subsequently became a professor of astronomy at Harvard University, who followed up the clue, and made himself master of a new department of astronomical science—rather, let us say, became the creator of this new branch, as well as its most assiduous cultivator.

New Sidereal Depths Sounded

No one can think of Cepheid Variables without at once thinking of Prof. Harlow Shapley.

The revelations that have resulted from the use of this new sidereal sounding-line in the hands of Prof. Shapley are nothing less than sensational.

Unimaginable depths of the heavens have been definitely sounded for the first time, by interpretation of the Cepheid Variable signals. The size, form, and structure of the galactic system and the distances of the globular clusters are gauged as was hitherto impossible, by observation of the pulsing Cepheids.

Prof. Shapley charts the system of globular clusters, and finds that some are 200 light-years away, others more than 200,000 light-years.

Cepheid Variables in the big nebula in the Constellation Andromeda locate that famous star-cloud at a distance of not far from 1,000,000 light-years.

And this is by no means the limit. Sir James Jeans makes quite casually a calculation which starts with mention that Cepheids whose light fluctuates in a period of 40 hours have approximately the luminosity 250 times that of the sun; and goes on to say that a Cepheid Variable of ten day period, with an apparent magnitude sixteen, from which we receive about as much light as from a candle at a distance of 10,000 miles is in reality 3,600,000 light-years away.

He adds that the "period-luminosity" law (as the Cepheid Variable method is called) "measures the distances of objects up to a million light-years away, with a smaller percentage of error than is to be expected in the parallactic measures of stars only a hundred light-years away."

The "parallactic measures," it will be recalled, are made by direct observation of a star from opposite sides of the earth's orbits. Stars 100 light-years away approach the limit to which this method is applicable.

Such measurements would have comparatively restricted value were they confined to the Cepheid Variables themselves.

But the value is enormously enhanced because these variables are usually situated, as already noted, in clusters or in nebulæ, so that the pulsating star signals not only its own distance, but the distance of thousands or millions of stars of the localized system in which it is found. Such groups may be in themselves hundreds of light-years in diameter, but such dimensions are negligible in contrast with the thousands or millions of light-years that separate the group as a whole from the earth—somewhat as one would neglect the difference between the near and far side of a football at a distance of a hundred miles.

The significance of this is made impressive by the estimate that names 50,000 light-years as the diameter of the Andromeda nebula. A big football, that!

The Pulsation Theory of Cepheid Variables

But while the Cepheid Variables thus signal distances across the inconceivable spaces of the universe, revealing their individual locations, what do the strange signals tell us of the character of the pulsating stars themselves?

It would be sensational news in the astronomical world if a definite and conclusive answer could be given to that question.

For the nature of the Cepheid Variables—the reason for their anomalous fluctuation in luminosity—constitutes one of the outstanding puzzles of Astrophysics, regarding which there has been abundant controversy, with no present prospect of agreement among authorities.

Of course explanations have been attempted. There are, indeed, two alternative theories, each with its prominent advocates, but neither, apparently, capable of explaining consistently quite all the observed conditions.

One theory is championed by Prof. Shapley and Prof. Eddington; the other by Sir James Jeans.

No one in the world feels quite competent to decide when such doctors disagree. But both theories are of interest and must be briefly summarized here.

According to Prof. Shapley's theory, which Prof. Eddington supports, the fluctuating luminosity of the Cepheid Variables is associated with an actual expansion and contraction of the bodies of the Cepheids themselves.

In other words, it is a veritable pulsation, like a heart-beat.

The fact that the light of the star, which is blue at the peak of luminosity, changes toward red on subsiding, supports the idea of an actual change in constitution of the structure.

It is obviously within the possibilities that a gaseous body may expand and contract.

The slowing down of the rate of pulsation with increasing maximum luminosity suggests some fixed relation between starage and the progressive change of constitution which determines the rate of expansion and contraction.

An Alternative Theory

All this seems plausible enough until we seek a cause for the sudden expansion by millions of miles of diameter to a fixed limit of a gaseous body, which immediately then begins to contract and as rapidly returns to the fixed minimum.

The attempt has not hitherto been convincingly successful. In the words of Sir James Jeans:

"The behavior of such masses of gas has been investigated mathematically by Eddington and others, but it does not appear that it can be reconciled with the observed behavior of Cepheid Variables."

The alternative theory, which Sir James himself advances, regards Cepheid Variables as bodies of ovoid shape, rotating, and on the point of fission—each a binary star in the making.

The variation in luminosity (in this view) is due to the presentation to view alternately of the long axis and the short—the broad side and the edge—of the ovoid body as it rotates.

Inasmuch as all celestial bodies are believed to rotate, and as double stars are exceedingly abundant (one-third of all naked-eye visibles are binaries, either visual or spectroscopic), and as such doubles are believed to have originated by fission, this suggestion seems highly plausible. It needs no higher mathematical support than that of its originator.

On the other hand, it does not obviously explain the recurrent changes of constitution of the star, as evidenced by its alleged change of spectroscopic character.

So the dumbbell theory, like the other, requires additional support.

The consensus of opinion seems to be that the final solution of the Cepheid Variable mystery is a problem for the future.

Novae, or New Stars

There are variable stars of other types that are no less mysterious. Long-term variables, for example, whose activities do not conform to those of the Cepheids, and regarding which it can scarcely be said that there is a current opinion as to their true character and the meaning of their variability.

Then, too, there are variables known as Novae, or new stars, which burst out from time to time in the heavens, sometimes attaining the brilliancy of planets, and then fade away in the course of days, weeks, or months. Such new stars have been occasionally observed, since the time of Hipparchus.

Tycho Brahe saw one, it will be recalled, and thought its appearance a miraculous event comparable to the standing still of the sun at command of Joshua or the darkness that came upon the earth at the Crucifixion.

Kepler saw one, too, and so did various of his great astronomical successors. Two notable ones appeared in the early years of the present century.

But nowadays they have ceased to be rarities, under perpetual scrutiny of the heavens with enlarged telescopic eyes. No fewer than eighty have been observed within recent years in the single structure of the great nebula in the constellation Andromeda.

As long ago as 1866, Sir William Huggins, the pioneer worker with the spectroscope, observed a new star, and saw that it had a spectrum of the solar order, with numberless dark lines, out of which shone brilliantly a few very bright lines. There was no doubt that at least two of these lines belonged to hydrogen. The great brilliancy of these lines as compared with the parts of the continued spectrum upon which they fell suggested a temperature for the gas emitting them higher than that of the star's photosphere.

These observations suggested to Huggins that some sudden and vast convulsion had taken place in a star so far cooled down as to give but little light, or even to be crusted over.

"Volcanic forces, perhaps, or the disturbing approach or partial collision of another dark star, had led to the escape of highly heated gases from within; and a chemical combination, after the gases had cooled by sudden expansion, gave rise to the outburst of flame at once very brilliant and of very short duration."

Possibly this speculation serves as well as another to explain a phenomenon which confessedly is by no means thoroughly understood.

The great Swedish chemist and cosmologist, Arrhenius, suggested an explanation not altogether dissimilar, to the effect that

a dark star plowing into a mass of nebulous matter sets up a conflagration which is temporary, or the effects of which are presently hidden by the great volume of combustion-products, which form in effect a smoke-screen, accounting for the rapid fading away of the star that had blazed up so brilliantly.

The observed fact of the relatively frequent appearance of the new stars in a nebula, as in the case of Andromeda just men-

FIG. 92.—Svante Arrhenius (1859-1927). (Crow-quilled from a sketch made from life at Stockholm in 1910.)

tioned, gives a measure of plausibility to the hypothesis of Arrhenius. But we shall require much more light on new stars before an explanation of their phenomena is made that will gain general acceptance.

The great significance of the new stars, in the early day, was to demonstrate to an astonished world that changes can take place in the supposedly immutable structure of the firmament.

Since, in the modern view, the whole universe is in a condi-

tion of perpetual flux, this aspect of the matter naturally has no significance.

The Algol Type of Variable

Another type of Variable star, and an exceedingly common type, has its typical representative in the well known star Algol.

This star, and others of its type, fluctuates in light, waxing and waning at regular intervals, which may vary from hours to days, months, or years.

The variability of Algol itself was discovered by the 18th century astronomer, John Goodricke, in 1782, just at the time when Herschel was beginning to make the stars famous. Goodricke's extended observations established the periodicity of the star as about "two days and nearly twenty and three-fourths hours."

This first observer of a variable star, or rather of the variation of a star, not only established thus its periodicity, but he went on to make tentative explanation of the strange phenomena.

Moreover, he found the correct solution, as was to be demonstrated more than a century later by Prof. H. C. Vogel, an authoritative worker in the field of spectroscopy.

"If it were not perhaps too early to hazard even a conjecture on the cause of this Variation," says Goodricke—and then goes on to hazard the conjecture, be it too early or not.

And the conjecture is that the phenomena observed, "could hardly be accounted for otherwise than either by the interposition of a large body revolving around Algol, or some kind of motion of its own, by which part of its body, covered with spots or such like matter, is periodically turned toward the earth."

The first guess was the right one. The variation of Algol, is due to the revolution about it of a companion star which, unlike itself, is not luminous. In 1880, prior to Vogel's spectroscopic demonstration, Prof. E. C. Pickering, of Harvard Observatory,

made a mathematical treatment of the star's orbit, based on the accurate photometric (light-measuring) observation of the light changes at the time of the eclipse—the particular field of work which Pickering had made peculiarly his own.

The spectroscopic testimony was required, however, to make demonstration complete.

Since it is known that double stars are the rule rather than the exception, it is not strange that variables of this type are exceedingly numerous.

The revolving couple may both be luminous, and yet the light may fluctuate when they are in alignment. Of course the orbit of a binary is only by chance so aligned with the earth that eclipse, partial or complete, occurs.

But this happens often enough to make variable stars of the Algol type by far the most abundant of all variables.

It is interesting to note in passing that the same astronomer, John Goodricke, who thus first studied the variability of a star, went on to discover variables of other types, notably the star called Beta Lyrae, a long-term variable whose vagaries are still not well understood, though shared by a considerable company of other variables of which this is the type; also Delta Cephei, type star of the Cepheids, whose peculiarities claimed our attention a few pages back.

Goodricke died too young to achieve popular fame, besides being overshadowed by William Herschel. But during his brief life he was a by no means insignificant figure in the astronomical world. No doubt the variable stars he introduced to the public had a certain share in developing popular interest, and in particular in spreading broadcast the conception that the "fixed" stars are by no means fixed and invariable.

Herschel himself also studied the double stars, as we have seen, and inferred from their observed occultations their regular swing in orbits explicable on the basis of Newton's law. It was this observation, indeed, that demonstrated the hold of the law of inverse squares on the sidereal bodies, no less than on the bodies of the solar system.

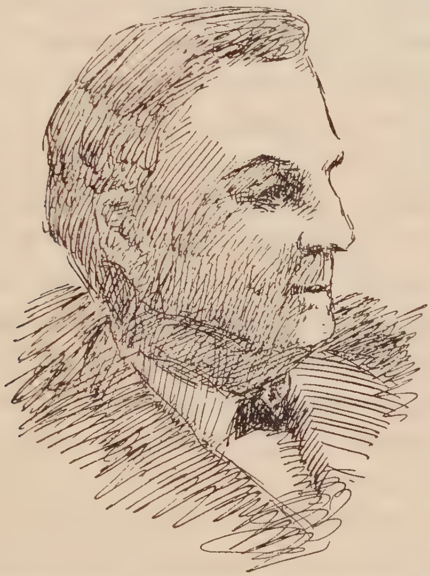

FIG. 93.—Sherburne Wesley Burnham. (Crow-quilled from a half-tone credited to *Popular Astronomy*.)

From that day to this double stars have had fascination for a long list of astronomers, including some distinguished amateurs, among them Burnham, the American, who personally discovered no fewer than a thousand doubles while still pursuing astronomy only as an avocation.

Double Stars by Thousands

In 1906 the Carnegie Institution published Burnham's complete list of all known double stars of the northern hemisphere

and to the thirty-first parallel of the southern hemisphere. Data are given for 13,665 stars.

Two stars that are close together may be only optically double, one star being far more distant than the other, and the two having no connection. Physically double stars are those that show a connection either by having a common proper motion or an observed orbital motion beyond their center of mass, the latter being known technically as binary stars.

Aitken and Hussey at the Lick Observatory have made an extraordinary survey of large portions of the northern heavens for double stars. Aitken's book on the binary stars gives the results of the scrutiny of a total of 100,979 stars, for which 5,400 proved to be doubles. Aitken himself had discovered 2057 of these, and W. Struve 1053. The conclusion is drawn that about one star in every eighteen as bright as the ninth magnitude in the northern sky is a double star as seen with the 36-inch Lick refractor. The proportion of double stars in or near the Milky Way is slightly greater than at a distance from it.

All this refers to visible doubles.

Reference has already been made to spectroscopic doubles, in binary systems, one member of which may be a dark star.

There is every reason to suppose that numberless stars have dark companions, though no data are available for a plausible estimate of the proportion of such. Of course the vast preponderance of the millions of stars revealed only by higher powers of the telescope are too faint to record spectrum lines by which their duplicity could be detected.

"Dark Star" seems a contradiction of terms. The existence of such bodies in the heavens, is an appealing paradox.

Are any of the dark stars afflicted with busy microbes that

might be classified as allied to the genus *Homo*? We can only surmise. It would be charitable to hope not.

But if there were such, even the all-seeing eye of the spectroscope could by no chance detect their presence.

The Trans-Neptunian Planet

The inadequacy of existing instruments to detect the existence of bodies of planetary size and mass, if there are such attendants on stars other than the sun, is emphasized by the observation that the trans-Neptunian planet discovered January 21, 1930, appears as a star of fifteenth or sixteenth magnitude, visible only in the field of the very largest telescopes. Then it appears merely as a speck of light, comparable to many millions of precisely similar specks. (Of fifteenth magnitude stars, the number computed is about 27,500,000; of sixteenth magnitude about 57,100,000.)

Yet the newly-discovered planet, though by preliminary estimate perhaps four and a half billion miles from the sun, is but stone's throw away from us, in comparison with even the nearer stars. The new planet is perhaps fifty times our distance from the sun. But the nearest stars, Alpha Centauri and its neighbor "Proxima," are at something over 268,000 times the sun's distance.

The light by which the new planet is photographed has come to us in perhaps seven hours. Light from the nearest star takes four and a third years to span the gap between us. And the star-flecks that lie on the plate surrounding the image of the new planet register light that may be scores, hundreds, or even thousands of years from its source.

In an earlier chapter we saw that a trans-Neptunian planet was suspected to exist not long after the discovery of Neptune itself. The calculations of the nineteenth century astronomers,

based on seeming perturbations of the course of Neptune, and on unaccounted-for retardations of certain comets, led to no definite result, but did not dispel the suspicion.

Prominent among the astronomers who were convinced of the existence of a disturbing outer planet, and who made elaborate calculations as to its probable place in the heavens in our epoch, was Percival Lowell, founder of the Lowell Observatory at Flagstaff, Arizona, an enthusiastic amateur of professional accomplishment, popularly known for his elaboration of the theory that the marks on the planet Mars represent areas of vegetation along irrigation canals.

This theory has not gained general acceptance, but the name of its chief proponent is assured perpetuity by the discovery, at the Flagstaff Observatory, fourteen years after its founder's death, of the trans-Neptunian planet, in the region where his calculations had located it.

The discovery was the result of specific search, made with a telescope especially designed for the work of photographing smaller stars. The light-speck representing the planet was first seen (close to the position of Delta Geminorum, a few degrees from Pollux) by a young photographer, Clyde W. Tombaugh, on a negative taken January 21st, and reported at once to the director of the observatory, Dr. V. M. Slipher. He and his associates confirmed the discovery, but did not make it public till several weeks later. Partly to make assurance doubly sure, partly perhaps for sentimental reasons, they withheld the announcement till March 13th, which is the anniversary of Herschel's discovery of Uranus (1781) and also of the birth of Percival Lowell (1855), whose life-work the discovery in effect laureated.

BOOK VIII

NEW COSMOLOGY AND COSMOGONY

"And I saw a new heaven and a new earth: for the first heaven and the first earth were passed away; and there was no more sea."

—*Oriental Anthology.*

XXXII

ADAMS—PEASE—HUBBLE—STAR NUMBERS AND DISTANCES

INTERPRETED by the Leavitt-Shapley "period-luminosity law," the Cepheids in nebulae appear to confirm the preconception that many of these, including all the spiral nebulae, are so remote that they may be thought of as "island universes," even as Kant and Herschel in the old days regarded them.

We shall see before we are through that there is perhaps another possible interpretation. But the conception of the spiral nebulae as island universes, or independent universes, outside our own universe, the galactic system, is the orthodox view of the astronomy of our epoch.

This view has been fortified not alone by Professor Shapley's studies of the Cepheid Variables, but also by another series of altogether remarkable observations, made in particular by Dr. W. S. Adams, of Mt. Wilson Observatory, in which the wizardry of the spectroscope has been put to a new and very strikingly successful test.

Again the Necromantic Spectroscope

Briefly, this amazing instrument, which hitherto had revealed the chemical composition of the stars and tested their line-of-sight movement, was to reveal also the parallax—that is to say the distance—of thousands of stars vastly too far away to be tested by the method of triangulation.

The method is based on the fact that when spectroscopic study was made of the lines in spectra of the stars of known distance,

it was found that in stars of the same type—giants and dwarfs of class M in particular—spectral lines that were faint in one were intense in the other. The numerical difference could be interpreted in terms of difference of absolute luminosity of the surface from which the light emanated.

In other words, here was a method of testing the absolute or actual luminosity of any star that could be spectroscopically photographed. And, as we have seen in connection with the Cepheid Variables, if actual luminosity can be known, a comparison with the observed apparent luminosity gives data for calculation as to the distance of the star under observation.

In the annals of the astronomer, it is found convenient to state star-distances from the earth in terms of parallax. But of course parallax can always be translated into the terms of light-years or of miles—though the last would involve the use of interminable rows of figures or of such meaningless phrases as "trillions of trillions."

The point of the moment is that this new method of spectroscopic parallax-determination reveals the distances of coteries of ordinary stars, just as the Cepheid Variable method revealed the distance of stars with which these anomalous bodies are associated.

Obviously the two methods could be used to check each other on occasion. It appears that their findings are, generally speaking, in accord.

The general result is that the astronomical world has become accustomed to the contemplation of sidereal distances which, were it not that they are altogether incomprehensible, would be utterly staggering.

A third method, which associates absolute luminosity with

mass, assuming that, surface for surface, stars of the same spectro type are of the same degree of brightness (a basic principle in Prof. Russell's celebrated scheme of stellar evolution) has supplemented the other methods. In a word, the attack on problem of star-size and star-distance has concentrated from many directions, and the new knowledge as to details of the celestial mechanism is bewildering in its profusion.

The technical character of most of these investigations makes it necessary for the layman to take their findings quite on trust, but confidence that the new estimates are by no means chimerical was justified (as noted in an earlier chapter) by the results of the direct measurement of the diameters of several of the largest stars—which were surprisingly in accord with dimensions predicated by the earlier estimates.

Methods of Star Measurement in Harmony

The direct measurement in question, made at Mt. Wilson by Dr. Pease with Prof. Michelson's wonderful interferometer, has been spoken of as the most notable achievement in practical astronomy of the present century.

But the method can be applied only to a few of the very largest stars that are relatively near, and after all its results are only corroborative—though in that enormously important—of the more comprehensive results of the application of the principle of period-luminosity in connection with Dr. Shapley's puzzling variables, the principle of spectroscopic parallax as applied by Dr. Adams, and the interpretation of Prof. Russell's principle of the relation between mass and luminosity among stars of the same spectroscopic type.

Spectroscope and photographic plate are still the chief accessories of astronomical equipment, as they were a generation ago.

But new methods of application, and new interpretations, have

so extended their field of usefulness, as to change the entire complexion of contemporary astronomical research.

It cannot be said that the new interpretation of the heavens involved is revolutionary.

Rather it is as if a powerful searchlight had been made to play on the old celestial mechanism, enabling the astronomer of our day to peer into its recesses with clear vision, where before there had been at best a twilight view or the fog of inadequately supported speculation.

The Number of Stars

The sidereal system as thus envisaged estimates the stars of our galactic system—the structure of which the Milky Way is the backbone—as numbering, probably, from 100 to 300 billion.

The former estimate is that of Professor Shapley, the latter that of Professor Eddington.

Such figures being totally without meaning for any mind, it makes no difference which may be nearer the truth; or whether some more modest estimates should be substituted.

Suffice it that the number of stars in our galaxy is inconceivably great.

I am not sure that concrete illustrations help one much toward a real comprehension of figures that so far surpass clear grasp of the imagination. But here are three or four illustrations that I have sometimes used.

Star Numbers Illustrated

Suppose that each star of the 100 billion in the galaxy were reduced in size to the mere needle-point that it seems—say to the size of a period on this printed page.

If, then, the 100-billion periods could be distributed single file, one after another in close contact, the line of periods would suffice to reach round the globe at the equator. If you try to imagine how many of these periods would be required to make

a line a mile long, and then imagine 25,000 such lines, you at least realize that we are dealing with a great many periods.

Again, suppose each one of our 100 billion stars to be the size of a silver quarter-dollar, and that the quarters were spread out in a close contact to form a mosaic covering the surface of the ground. There would be enough of these quarters to cover 250 square miles, or a surface 16 miles square. That would be a great many quarters.

If we suppose each of the quarters magnified to a diameter of nine feet, we should then be able to make a solid mosaic covering the entire surface of the United States.

Finally, if each of our stars had a diameter of 38 feet—the length of a biggish room—the aggregated supply of such paving stones would put a solid layer over every mile of the land surface of the globe.

But after we are through with all such illustrations, I am inclined to think that by merely glancing at a photograph of a portion of the Milky Way—realizing that this represents a tiny spot of sky in the midst of the immensity of the firmament—one gains a more overwhelming sense of the number of the stars than can be gained from any imaginary transposition of the stars to the surface of our infinitesimal planet.

Whither Are We Bound?

No one doubts nowadays that all these stars are in motion, though the movements of only a few thousand have been accurately charted.

Of course our sun moves along with the rest, and the direction of its flight—carrying the planetary system with it—has been accurately charted by noting the direction of apparent movement of the nearer stars which appear to shift backward

in comparison with more distant stars, just as telegraph poles from a car window shift back against the distant landscape.

Another method of testing the sun's flight is spectroscopic. By noting the apparent speed of approach of a given star at different periods of the year, a difference may be observed (in case of a star properly located) which may be interpreted as movement of the observer through space. Of course, account must be taken of the known movements of the earth, rotational and orbital.

But a residual movement may remain which is to be interpreted as flight through space of the entire solar system.

The so-called apex of the sun's flight, as determined by these various tests, is located toward the bright star Vega—which will one day be the pole star.

The most accurate designation of this apex of the sun's flight is held to be that made by Lewis Boss, based on investigation of the proper motions of more than 5000 stars.

The exact position, as he determined it, is given as Right Ascension 18 hours 2 minutes; Declination, plus 34.3 degrees.

A slight departure as to the declination is shown by the investigations of Campbell and Moore of the Lick Observatory on the radial velocities of more than 2100 stars. In one part of the sky the stars on the whole are approaching, in the opposite part they are receding, while in the region between, they are, on the average, doing neither. They find the point toward which the sun is moving to be Right Ascension 18 hours 2 minutes, in agreement with Boss, but Declination 29.2 degrees—a difference of 5 degrees, or 10 apparent diameters of the moon.

It is of interest to recall that the newest estimate of the direction of flight of our sun with its attendant planets varies by only

a very small angle from the direction estimated more than a hundred years ago by Herschel—whose inspired guess had foundation in observation of only seven stars of observed proper motion, as against the thousands at the service of the modern cosmologist.

Herschel's estimate of the form of the galactic system, and his conception of the nebulae as island universes lying beyond our system, also find confirmation in the elaborated investigations of the modern astronomer.

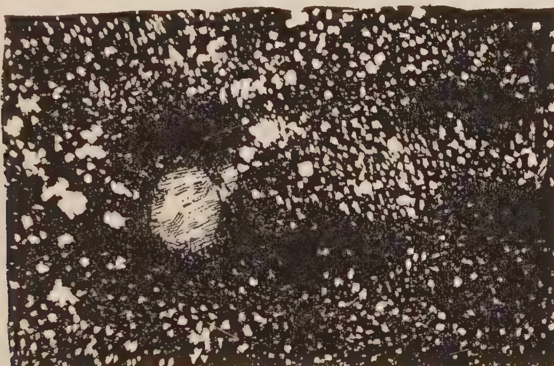

FIG. 94.—A Planetary Nebula and Dark Nebulae. (Adapted from a photograph credited to Prof. M. Wolf.)

When structure of this universe is in question, the nebulae always come in for a full share of attention. The Mystic Nebulae

Nebulae belong essentially to modern astronomy, since despite their enormous actual size, they are so distant from the earth or so faintly luminous as to be telescopic objects only, with the single exception, in the northern hemisphere, of the aforementioned great nebula in the Constellation Andromeda.

This is faintly visible to sharp eyes as a small patch of light, comparable to numberless nebulosities of the Milky Way—the

latter being, in part at any rate, merely groups of more distant stars.

In addition to such apparent nebulosities, there are, of course, numberless actual nebulae located in the Milky Way, subject only to observation with the telescope, and satisfactorily observable only with telescopes of high power. Indeed, there are two main types of nebulae and several sub-types, that are found almost exclusively in or near the Milky Way, and which are therefore known as Galactic Nebulae.

FIG. 95.—Trifid Nebula in Sagittarius. (Crow-quilled from a photograph of untraced origin.)

As classified by Dr. Hubble, these are called planetary nebulae and diffuse nebulae.

Of the latter type—the filmy structures familiar in stellar photographs—some are predominantly luminous, others so obscure that they make apparent dark places in the midst of the star pictures; yet others conspicuously mixed, luminosity alternating with obscurity, in a way to suggest diffusion of a nebulous structure.

The great nebula in Orion, the Trifid nebula in Sagittarius and the network nebula in Cygnus are familiar illustrations of diffused Galactic Nebulae.

Planetary and Spiral Nebulae

Planetary nebulae are so named because with telescope of low power they appear to have a small disc, like that of a planet, with a fairly well-defined edge. They are, however, of more intricate form as viewed with higher powers. The so-called ring nebulae usually have a focus of light, like a bright star, at the

FIG. 96.—Network Nebula in Cygnus. (Crow-quilled from a photograph of untraced origin.)

center of the target-like ring or bull's eye within the annulus of nebulous light.

These look more like rings of smoke which some tobacco users puff out than like any other familiar object.

The so-called extra-galactic nebulae are sometimes of irregular form, but more commonly take the shape of fairly regular ellipses, or else of spirals.

The two types are held to be closely similar in character. Exceptional interest attaches to the spiral form which is, as we

have seen, regarded by some highly competent observers as a world-system in process of evolution.

Both types have well-defined centers of high luminosity, which are, according to one theory, vast aggregations of stars, but which no present telescope can resolve into individual particles of light.

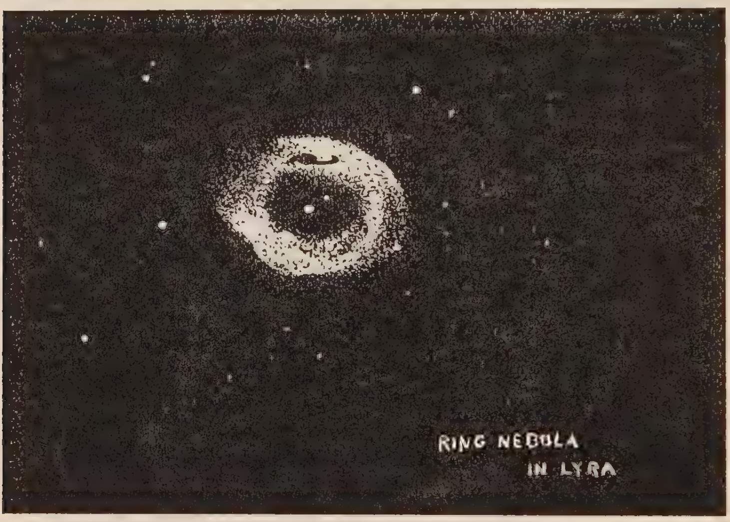

FIG. 97.—A Typical Ring Nebula. (Redrawn from a photograph of untraced origin.)

It is highly interesting to note that the prevailing twentieth century opinion as to the spiral nebulae is that they lie at enormous distances (even as distances are counted in the sidereal world), and actually beyond the bounds of our galactic system.

That they are, in a word, "island universes," just as Herschel thought them, and as Kant conceived them away back at the middle of the 18th century.

The seeming rotation of the spirals, which has been assumed

to represent an actual revolution of the component stars and nebulosities of the arms, or indeed of the entire structure, has been verified by the critical observations of Van Maanen, who compared photographs taken at Lick and at Mt. Wilson Observatories from ten to seventeen years apart.

Rotation of Spirals Verified

He finds in several cases evidence of the change of the positions of small condensations in the nebulae with respect to stars in the vicinity.

He infers a movement of matter from the nucleus along the arms of the spirals and a rotation of the arms about the nucleus. Dr. Lundmark confirms this. But one observer makes the speed of the shifting masses 16,000 miles per second, the other only 1500!

The direction of rotation in each instance is not what it looks like to most eyes in the picture, but what the current theory as to the origin of the structure would lead one to expect: the curved arms are swinging with their concave sides forward—as if winding about the nucleus.

Meantime the spectrographic method has been applied in the endeavor to test the rotation of the arms of spiral nebulae by Slipher, Pease, Wolf, and Wright (I quote here Professor E. A. Fath, of Carleton College):

Their results show material to be moving away from the nucleus. But they find the velocity to be of the order of only 200 miles per second.

The discrepancy between 200 miles 1500 miles and 16,000 suggests that results hitherto attained are only tentative. This is peculiarly apparent when it is added that Drs. Van Maanen and Lundmark (as Professor Smart remarks) made their divergent measurements on the same plates.

Unfortunately the chance to check one method by the other is not quite all that could be wished, because the nebulae best suited for the spectrographic method, that is to say, those whose planes are inclined at a small angle to the line of sight, are the ones least suited to detect displacement by direct measurements of the photographs. For obvious reasons, those whose planes are most nearly at right angles to the line of sight are best suited to the second method.

FIG. 98.—Great Nebula in Andromeda. (Crow-quilled from a photograph made at Yerkes Observatory.)

About 500 nebulae of the spiral class have been thus critically observed, ranging in size from the great Andromeda nebula, which is about two degrees in length, or four times the apparent diameter of the moon, to objects so small as to show a definite spiral structure only upon careful examination.

But the large ones on small-scale plates are closely similar to the small ones on large-scale plates.

Apparently size is held to be largely a question of distance.

Prof. Fath, working with plates taken with the sixty-inch

reflector of the Mt. Wilson Observatory, illustrates graphically the long-observed tendency of the spiral nebulae to cluster about the galactic poles—that is to say, the relatively bare spaces of the sky in rectangular relation to the plane of the Milky Way.

He shows further that the clustering is more marked around the northern than around the southern galactic pole; and that the clusters tend to focalize in opposite quadrants of the celestial sphere.

He suggests the possibility, however, that the seeming avoidance of the Milky Way by the spiral clusters may be only an optical effect, due to the obscuration of these distant and faint bodies by the brighter light of the galaxy.

"For the present," he adds, "it seems best to accept the apparent distribution as an observed fact and await further light on the subject."

Distances of the Nebulae

Prof. Fath, among others, has made somewhat careful estimates of the total number of nebulae observable in the entire sky.

He states that no attempt has been made by anyone to make a really accurate count, but cites the estimate of several other observers in which the aggregate census varies from 120,000 to more than 1,000,000.

His own opinion is that, for the present, the number of nebulae within reach of the largest photographic telescopes may be taken provisionally at from one-quarter to one-half million.

No nebula has been clearly shown to have a visual parallax, from which, as from other evidence, it is inferred that nebular distances must in general be measured in terms of thousands of light-years.

Dr. Hubble, from study of the Cepheid Variables in Andromeda, estimates the distance of that nebula at 700,000 light-

years. And this is presumed to be perhaps the nearest member of the family.

If the extra-galactic nebulae are of the same general order and size and luminosity (a rather hazardous inference, perhaps, but one to which many astronomers are committed) then the smaller of the photographic images represent nebulae of distances that make the farthest galactic stars seem neighborly.

Dr. Hubble estimates the distance of some of the smallest at 80,000,000 light-years!

He estimates also that with long exposure the one hundred-inch reflector at Mt. Wilson Observatory might record objects at a distance of about 145,000,000 light-years.

Meantime Professor Shapley reports that some of the Harvard plates show a group of nebulae in the region of Coma-Virgo which may be as much as 100,000,000 light-years distant.

Nothing neighborly about such spiral nebulae as these!

Light-Years in Terms of Thread

Notwithstanding the skepticism I have previously expressed as to the value of such illustrations, I am moved to present the result of an attempt I sometimes make to bring the imagination of a popular audience to grips with the implications of "100,000,000 light-years."

I ask the audience to endeavor to imagine a cable of fine silk thread stretched out from the earth to the star that is 100 million light-years distant.

I ask them to assume then that the earth, in spinning, winds the thread about it at the equator, as one winds a spool of thread or a skein of yarn.

I do not ask my auditors to endeavor to imagine the length of time that would be required for the spinning globe to wind up the entire cable of thread. I ask them merely to assume that this

span has elapsed and that the thread is wound about the globe tightly, as a spool of thread is wound.

I ask them to imagine that the surface of the globe on which the thread was wound is 4000 miles in width, covering thus something more than the entire tropic zone.

Then I tell them that there would be enough of the thread to cover this surface—making a great belt 4000 miles wide around the entire globe—not once merely, but a thousand times.

In other words, the earth-spool would have tightly wound about it 1000 layers of thread across the entire breadth of 4000 miles and stretched round the 25,000-miles circumference.

Again I am not very certain that such an illustration greatly helps.

Still, no one can contemplate that 4000-mile-wide girdle about the protuberant waist-line of what, from the human standpoint, seems a very large planet, without gaining the impression that a great deal of thread has been required to plumb the depths of 100 million light-years.

XXXIII

KAPTEYN—EASTON—SHAPLEY—THE STRUCTURE OF THE UNIVERSE

LET us now endeavor to gain an impression of the mechanism of the stellar system that requires such a cable for its sounding, as revealed to, or interpreted by, the modern astronomer.

Let it be said at once that the envisagement of this celestial mechanism does not require us to change very markedly the mental picture derived from contemplation of the grindstone universe of Dr. Wright, exposited at the middle of the 18th century, or the allied systems of his contemporaries Lambert and Kant—conceptions that the elder Herschel elaborated and made familiar to the generation that saw the beginning of the 19th century.

The familiar figure then suggested—a grindstone—or even better an ordinary watch, may be cited as fairly representative of the shape and form of the galactic system, which is usually referred to as the universe.

The galaxy itself, or Milky Way, represents the plane of the equator of the system, and it seems to form a nebulous coil of stars circling the heavens, chiefly because it represents greater sidereal depths than are viewed in other directions—as if one's position were not far from the center of a watch, and necessarily at a greater distance from the circumference than from the two flattened sides.

As to our precise location in their lens-shaped galaxy, the modern estimates are somewhat different from the estimate of Herschel. He opined that we might be fairly near the center. The modern estimate removes us considerably from that location—being more nearly in agreement in this regard, it may be added, with the estimate of Lambert, who on the basis of utterly inadequate evidence, made the sagacious speculation that the actual center of the galactic system lies at a remote distance from our sun.

Lambert suggested Orion or Canis Major as the possible cen-

ter. The modern astronomers do not closely agree with Lambert or with one another, as we shall see.

But the modern estimates are confessedly only tentative. No very convincing evidence is available to determine the precise bounds of the galactic system, notwithstanding the agreement as to its general outline.

It is argued that since the Milky Way is practically a great circle in the sky (a "great circle" in the technical sense is a circle whose plane cuts the center of the sphere or spheroid), the sun must lie close to its plane.

One Hundred Light Years a Neighborly Distance

The meaning of "close," however, calls for elucidation. According to Gerasimovic and Luyten, as cited by Professor Fath, the sun's distance from the plane of the Milky Way may be estimated at 33 parsecs—about a hundred light-years.

Not so very "close," then, in the ordinary acceptance of the word.

But this distance, be it understood, refers to the plane of the Milky Way and not to the center of that plane. The sun's distance from the center is held to be very much more significant. But as to just what the figure should be, authorities are by no means agreed.

We are told that, as regards the location of the center, Kapteyn, guided by his studies of star-drift, favors the region of Cassiopeia, while Shapley, whose Cepheid-Variable and Globular-Cluster studies have made him thoroughly at home in the universe, thinks the Scorpius-Sagittarius region the more probable one. Yet other astronomers, notably Easton, favor the direction of Cygnus.

Finding here a range of right-ascensions of six hours or so, and a range of declinations covering half a hemisphere, one's

mind reverts to the estimate of the sagacious Lambert, and one wonders whether his guess, perhaps, may not be as good as another.

Meantime, one is prepared to learn that the authorities are not well agreed as to the probable distance of the sun from the center of the galactic system—which is no more than might be expected, inasmuch as they so radically disagree as to where that center is.

We are told that Kapteyn has given a provisional estimate of 650 parsecs but that Shapley's work shows rather conclusively that this is too small. His estimate is 16,000 parsecs—a 25-fold increase.

A difference of 50,000 light-years cannot be regarded as quite insignificant, even in charting the universe. But fortunately the discrepancy means nothing so far as actual comprehension is concerned of our relation to the galactic system.

Let it suffice that the authorities are agreed that the sun lies a long way from the geographical center of that system.

Our Annual Shift of 367,000,000 Miles

A partial explanation of the discrepant estimates of the sun's precise location in the galactic system is to be found in the fact that the study of star movements on a large scale is a comparatively recent development of astronomical science.

The present situation can be understood only if we reflect on our shifting relation to the stars, as regards actual position in space.

One thinks naturally of the shift of position of the human observer due to the rotation and revolution of the earth. But in the larger view these changes are relatively insignificant. The earth-spin carries the observer round and round in a circle of 4000 miles radius. The revolution of the earth carries us round

the sun in a circle of nearly 93,000,000 miles radius, obviously the widest base line we can use in testing the parallax of a star by the trigonometric method.

But now reflect that the earth, along with the sun, goes forward in a direct line (or conceivably along the arc of an enormous circle) by 367,000,000 miles in a year (about 12 miles per second), and that this shift is added to by a like amount each succeeding year.

If, then, we consider observations made back in the old Alexandrian days by Hipparchus and compare them with observations made in our own time, we have records of the star-maps made from two points of view that differ by 367,000,000 times the number of intervening years.

The shift of a single year is the equivalent of almost twice the diameter of the earth's orbit. The seeming backward drift of a star that lies near enough to show parallax must therefore be about twice the amount of the parallax. In ten years, this backward drift, or "proper motion" of the star would be twenty times its parallax; in a hundred years, two hundred times the parallax.

This being clear, we understand why proper motion was discovered long before parallax could be measured, and why the comparison of present-day observation with star-charts, not merely of Hipparchus, but of Bayer, Tycho, Flamsteed, Bradley, and even much more recent observers, gives records of proper motions by thousands.

Star Streams Discovered

It is the collation of this almost inexhaustible material that has given the modern cosmologist such insight into the movements of the stars as could not otherwise be attainable.

Primarily these observations refer to the apparent movement

of stars, independent of their actual motion. But it is obvious that the actual motion of the stars may complicate the backward drift, and that comparative data may enable the observer to separate one motion from the other. Then the spectroscopist steps in to test the line-of-sight motion of the star.

A combination of the two sets of observations reveals, finally, the actual movement of the star in three-dimensional space.

Collation of such records has revealed that, by and large, the stars are arranged in great groups or clusters, moving through space in various directions, like flocks of birds, or swarms of bees.

The great Dutch astronomer Kapteyn made laborious microscopic measurements of the location of about a quarter of a million stars on numberless photographic plates, and was thereby led to discover that two great star-streams, comprising not less than half a million members, including most of the brighter stars, have met and mingled like counter-currents in the region of space in which the solar system at present happens to be.

An Englishman, H. C. Plummer, made the same discovery through independent observation almost simultaneously.

These vast star-streams are moving in nearly opposite directions in the plane of the Milky Way. But they do not include the stars of the Milky Way itself. The myriad clusters that make up that galaxy lie far out beyond the star-streams. So distant are they that they show neither proper motion nor parallax nor actual motion. For the most part they are too faint to be tested accurately with the spectroscope.

The actual forms of the streams or clusters into which they appear to be grouped are as yet only matters for conjecture. Their average distance is roughly computed at a neighborly three thousand light-years or so. Even at that, if they had been blotted

out of existence in the days of the mightiest Pharaohs of Egypt, they would still shine for us just as they do.

Neighborly Groups of Stars

If we view the galaxy of stars from yet another standpoint, asking what has been revealed as to the ultimate structure of the cosmic mechanism, we learn that a combination of methods, in the hands of many observers, has given some extraordinary glimpses into the arrangement of at least those portions of the universe that lie somewhat within our neighborhood.

Considering first our immediate environment in space, it appears that our sun, with its inconsequential planetary attendants, is one of a company of seventeen stars making up a rather compact cluster about ninety-five billion miles in diameter,—roughly one million times the earth's distance from the sun. Seven of these stars are doubles. Five of them are brighter than the sun; yet all are comparatively dim, the brightest being only forty-eight times brighter than the sun; whereas there are more distant stars in the sky that are ten thousand times more brilliant.

Going out beyond the confines of our immediate star cluster, we find various interesting groups at what might be called—gauging our mind to stellar magnitudes—moderate distances.

There is, for example, a neighborly cluster of forty stars in the constellation Taurus, between the Pleiades and the bright yellow star Aldebaran, that Professor Lewis Boss, of Albany, watched with tireless assiduity for many years, using the proper motions alone, and not the spectrographic method. By laborious calculations he removed one source of error after another, until finally he could assure us that the stars of the Taurus cluster are moving through space together in parallel lines at uniform speed, like a flock of birds.

They are 120 light-years (800 million million miles) away;

but they passed us at half that distance about 8,000 centuries ago—observed, perhaps, but not recorded by star-gazers of the Rough Stone Age.

Then there is a cluster of seventeen helium stars in Perseus; and another cluster of thirteen stars in the Great Bear, which seem to lie in about the same plane,—each cluster pursuing its own independent way, apparently quite unaffected by other stars that may chance to have wandered into the same territory.

As to the Great Bear cluster, it is rather surprising to learn that of the seven conspicuous stars forming the "big dipper," five are moving uniformly in one direction and the other two with equal uniformity in quite another direction.

The familiar figure of the "big dipper" is therefore in part an optical illusion which will not maintain its shape throughout future ages.

In due course the "pointers," for example, will cease to point to the pole star. But the pole itself is shifting as our little globe wabbles through space, so this does not greatly matter. Some 12,000 years from now Vega will be the pole star, and no pointers will be needed to indicate that brilliant object.

At far greater distances in space there are groups of stars of the Orion or helium type, which have a characteristic spectrum suggestive of a recent origin. These are sometimes grouped into luminous clouds like the Pleiades and the diffused nebulosity in Orion.

Some of these stars have enormous absolute brilliancy. Rigel in Orion, for example, shines at first magnitude. Were it no brighter than our sun it would appear only as a telescopic star of tenth magnitude.

Relative Sizes of the Suns

We have just spoken of the dazzling brightness of some stars in comparison with our own particular star.

It must be explained, however, that brightness is not to be confused with actual mass. There is a rather definite, and for the astronomer highly useful, relation between volume and brightness, but a star of enormous size may be so tenuous in structure that its actual mass is no greater than that of a star of only a fraction its diameter.

This is obvious enough, but few astronomers, perhaps, suspected how entirely fallacious the test of size is in estimating the mass of a star until Professor Eddington made a computation in which, for graphic effect, he postulated a series of gaseous spheres, the first containing ten grams, the second one hundred grams, the third one thousand grams, and so on.

Number 1 weighs as much as a letter, number 5 as much as a man, number 10 as much as an ocean liner.

Nothing startling so far. But now, going up the scale, to reach numbers 30 and beyond, comes the surprise. For it appears that all the stars whose masses are known lie between numbers 33 and 35 of the scale. And nearly all lie between numbers 33 and 34.

Eddington's calculations show that, until we come to sphere 33, light-pressure is nearly negligible compared to gas expansion; and after we reach sphere 35, gas expansion is nearly negligible compared to light-pressure.

At this point, then, in Eddington's picturesque phrase, we should expect "something to happen." And "what happens is the stars."

Masses smaller than number 33 do not grow hot enough to shine. Masses larger than number 35 are too unstable because radiation pressure bursts them asunder.

Sphere 33 is of half the mass of the sun, and sphere 35 has fifty times the sun's mass.

In general terms, then, it may be said that a star whose mass is one-tenth that of the sun would never become a self-luminous body, though it might exist as a dark star, while a mass one hundred times that of the sun either could not form at all, or would be broken up because the disruptive forces due to the high temperatures developed would exceed its gravitational force.

Baby Giants and Senile Dwarfs

The astonishing tentative conclusion is, then, that luminous stars are limited in mass to a range of from about one-tenth the mass of our sun to one hundred times that mass.

It is pointed out that this theoretical calculation is sustained by the observation that the star of least mass known (at the moment) is, according to Aitken, of a mass one-fifth that of the sun, while the star of greatest mass is a double, with components approximately 86 and 72 times the sun's mass.

The smallest star in question is the companion of Krueger 60.

The heaviest star is known as B. D. plus 6°1309. It may be more popularly described as Plaskett's star, having been discovered in 1922 by Professor J. S. Plaskett, of the Dominion Observatory.

Mr. Otto Struve's particular star, discovered in 1927, appears to be a quadruplet, with aggregate mass calculated as 950 times that of the sun. If confirmed, the mass of this star contradicts the Eddington calculation—or represents an exceptional departure from precedent.

Even so it appears that the words "giant" and "dwarf" apply to stars only in a relative sense. There is no such discrepancy in actual size of stars as there is in apparent size.

Of normal stars as of normal human beings, it might be said that all are of an "average" size.

Moreover, the greatest discrepancy between the smallest and largest stars (as hitherto computed) is no more than that between human beings at different stages of their career. There is this difference, however, that baby stars bulk large, while old stars are small. Giant stars are young and dwarfs are old. The giants make a brilliant appearance, but they are really great clouds of gas.

Young Stars Move Slowly

Now we begin to understand how it is that the brilliant Sirius gives 10,000 times more light than its dwarf companion, and yet is really only three times as heavy as the dwarf.

We have an inkling as to why stars of the same type—that is to say, the same age—tend to be grouped in the sky in great scattered clusters.

We can picture a time when each such cluster was a vast cloud of primordial gas, its portions being first drawn together by gravitation, and then, heated by this process, scattered by radiation into more or less isolated clouds, each of which ultimately underwent condensation to produce an individual star, or smaller group of stars.

We even have an inkling as to why, on the average, young stars are drifting through the universe at relatively slow speed, as compared with old stars—why, in a word, star speeds are progressively more rapid in the successive classes from O and B through the descending scale A, F, G, K, to M.

Campbell and Moore, for example, found the average radial velocity of the B (young, hot) stars they examined to be 8.7 kilometers per second, while the M stars moved almost twice as fast—16.1 kilometers per second.

Correspondingly Boss, by observation of proper motions, found class B stars moving 2.8 seconds of arc per century while M stars move 5.0 seconds per century.

Fath summarizes these facts with the statement that: The more massive stars have smaller velocities than the less massive. He adds, with true scientific caution, that we need additional facts before we shall have an adequate explanation.

Abandoning caution one might suggest (as, indeed, was suggested in an earlier chapter) that the big young stars are nearer the stage when their substance was part of a vast cosmic cloud in which gravitation tending to pull the substance together and radiation tending to separate it oscillated and, as it were, fought for mastery. The old stars evidence that the battle was finally won by gravitation, which subsequently was to drive the stars, age after age, faster and faster in their fall toward some gravitational center of the universe, or in a comet-like circuit about such a hypothetical center.

But this of course is purely conjectural.

Our Galaxy a Spiral Nebula?

Explanations aside, however, the facts of star-movement and star-clustering, accumulated through the joint endeavors of scores of modern observers, enable the more imaginative astronomers of our day to conceive at least in vague outline the scheme of the galactic system and of what they believe to be outlying portions of the universe.

The schemes of no two theorists precisely agree, yet there is basic uniformity in the conception of the watch-shaped galactic system, with the great body of the stars circling about its circumference.

Strömberg emphasizes the existence of a "preferential way"

(somewhat along the plane of this system) through which great flocks of stars tend to migrate.

Easton sees in the galactic system a giant spiral nebula, with the center of the spiral somewhere in the direction of the constellation Cygnus.

In this view, our galaxy is one of the system of spiral nebulae, rivaled in size perhaps only (in Shapley's view) by the companion "super-galaxy" Coma-Virgo—the other spirals being, to these, as islands to continents.

The "other spirals" in question are distributed (as we have seen) to the number of 100,000 or ten times that, about the poles of our galactic system. That is to say, they occupy the relatively starless spaces at right angles to the plane of the Milky Way.

Dr. H. D. Curtis, as cited by Dr. Abbot in his book "The Earth and the Stars," presents an attractive diagram (here reproduced) of this scheme of the great spiral of the Milky Way, which we call the stellar universe, and these telescopic spirals which have come to be spoken of as "island universes."

The same conception is represented in pictorial diagram by a lens-shaped group of stars long familiar.

The Lambert-Shapley Universe

In November, 1929, Professor Harlow Shapley presented before the American Academy of Science an outline of perhaps the most comprehensive interpretation of the cosmic scheme hitherto attempted.

Professor Shapley estimates the diameter of our watch-shaped galaxy at about 300,000 light-years; with thickness at about 10,000 light-years.

He brings the objects of the entire universe into a serial scale, ranging from the world of the almost infinitely little to the world of the almost infinitely great.

THE FACTOR OF SPACE DISTRIBUTION

100,000 ± Spiral Nebulae

Distance unknown

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The Milky Way and stellar universe
is believed to be roughly lens-shaped and
about 3,000 by 30,000 or more light-years in extent. In
this space occur nearly all the stars, nearly all the diffuse neb-
ulosities, nearly all the planetary nebulae, nearly
all new stars, nearly all clusters, nearly
all the valuable stars, etc., but
NO SPIRAL NEBULAE

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100,000 ± Spiral Nebulae

Distance unknown

This graphic presentation of the universe-plan is credited to Dr. H. D. Curtis by Dr. C. G. Abbot, from whose book "The Earth and the Stars" it is here transcribed. A footnote states that "Hubble has since proved

that several spirals are about a million light-years away." The word "proved" is perhaps incautious.

At zero, as a starting point in either direction, he places the satellite system, of which our own earth-moon system is a type.

Grading downward, he ranges from meteoritic associations (comets, meteor streams, diffused nebulae) through microscopic molecular aggregates to atoms and corpuscles.

Ranging upward successively are planetary structures (stars to ringed nebulae), double and multiple stars, galactic clusters, globular clusters, star clouds, galaxies, super-galaxies (here our home galaxy) groups of super-galaxies, the "cosmoplasma" (cosmic meteors, diffused nebulosity, radiation), and the universe (the "space-time complex") as a whole.

That no one may suppose he thinks discovery at an end, Professor Shapley leaves a numbered blank space at each end of the series, to be filled in by investigators of the future.

Professor Shapley of course illustrates his system with a wealth of documentation.

Here it suffices to give the outline, and to note that a place is provided for every type of sidereal structure hitherto observed. A particularity of the scheme is the introduction of super-galaxies, of which the home galaxy is one; and of "groups of super-galaxies," which include double groups and complex assemblages.

Here, then, we have what might be called a documented and scientific elaboration of a scheme of minor and major systems of star groupings of which the genius of Johann Lambert had premonitory vision at the middle of the 18th century.

The system of the Milky Way, a flattened cylinder or spheroid; systems of higher order (our earth belonging "by a chain of gradations, to several systems, and at last to the system of the

universe"); the Milky Way, comprehending several systems of fixed stars, each system with its own center; the "assemblages"—all these are adumbrated in the cosmologic dream of the contemporary of Wright and Kant, each of whom (it may be added) entertained not dissimilar dreams.

The difference is that the older cosmologists were groping in the dark, jumping to conclusions, drawing inferences from casual inspection of the stellar picture that could rank only as dreams —however close to inspiration.

But the modern cosmologist, elaborating these dreams of his forebears of the elder day, documents them, fortifies the speculations by an almost bewildering array of evidence garnered by new instrumental means—so that what was aforetime almost fantastic speculation becomes in our day secure (though of course still provisional) scientific hypothesis.

In a word, the old cosmology was a vague fantasy, the new cosmology is a structure clearly depicted as to its major outlines.

The Ultimate Plan Not Revealed

But the new cosmology has nothing convincing to say about the ultimate plan of the structure whose details of movement are revealed on so large a scale.

Whether, as Lambert conceived, there is a common center about which all the bodies of the universe revolve—or, better said, all the universes—remains for the cosmologist of the future to determine.

The most penetrative vision of today shows us innumerable systems of celestial bodies moving this way and that. But so far as the evidence goes there is no determinate coordination between these movements.

The spectroscope seems to show that the spiral nebulae—those outlying "island universes"—are for the most part rushing

off into space away from our galactic system, at speeds ranging from a few hundred to perhaps two thousand miles per second.

The evidence may not be altogether conclusive, but such as it is it suggests, not a universe being coordinated, but one being dissipated.

In a word, the modern Cosmos has not passed beyond the stage of Chaos.

In a later chapter, we shall have occasion to inspect this chaotic cosmos from a new angle.

We shall see that it is possible at least to raise the question as to whether the interpretation put upon the seeming isolation of the alleged island universes, and the almost equal isolation of some other nebulae and star clusters, is of necessity valid.

We shall see that it may be questioned whether the telescopes of the astronomer can extend his vision by any possibility beyond the confines of the particular system which we call our universe; whether, in short, these "islands" are not necessarily smaller than our "continent" because they are a part of it.

The enigma implied will be explained in due course.

Meantime the orthodox view of the new heavens is that which has just been summarized.

For the authoritative leaders of our time, the estimate which substitutes "parsecs" or parallaxes for the too-short unit "light-years," and juggles trillions and quadrillions as confidently as ordinary usage deals with hundreds and thousands, represents secure actualities of the celestial mechanism—of the new heavens.

XXXIV

OLD COSMOGONIES AND NEW

"And God made two great lights; the greater light to rule the day, and the lesser light to rule the night; he made the stars also. And God set them in the firmament of the heaven to give light upon the earth."

—*Genesis I*, 16, 17.

"He made the stars also." Doubtless that is the most concise description of a great historical event in all literature. Even Caesar's famous epigram, in the English translation, requires six words. Here are only five. Yet the event described, as interpreted in the light of modern knowledge, involves the creation of perhaps a hundred billion suns, each one the equivalent in bulk of hundreds of thousands or even thousands of millions of globes like the one on which we live.

The ancient cosmogonist dismisses this really stupendous feat with a dash of the pen, and does not return to it. The five words do not even stand as a sentence by themselves; they are only the tag end of the sentence that describes the making of the "two great lights; the greater light to rule the day, and the lesser light to rule the night."

Even a casual reader might suspect that the ancient poet did not know the true relation of his greater and lesser lights—the sun and moon—to the bodies included in the minor clause of that seeming after-thought: "He made the stars also."

The modern cosmogonist, enlightened by the telescope, reverses the picture. When he speaks of creation, he thinks first in terms of stars, and only incidentally of the minor star called

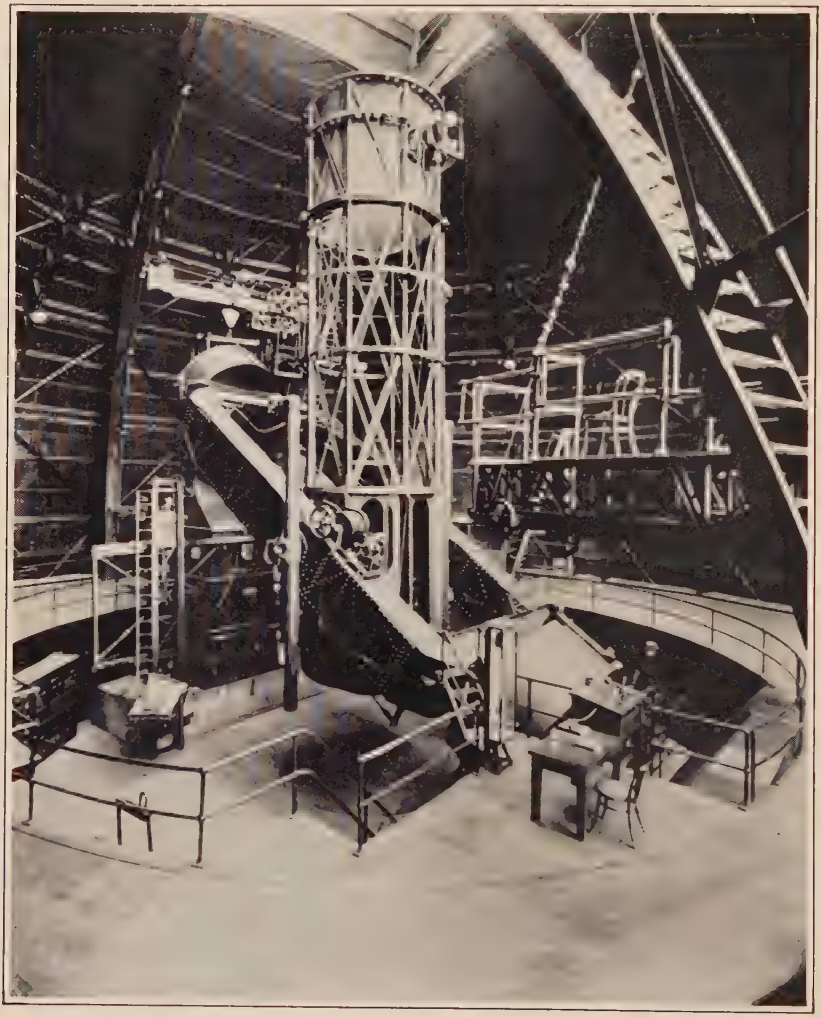


Plate XXI: The 100-inch Reflector of Mt. Wilson Observatory

the sun, with the insignificant planet earth, and the negligible fleck of residual star-dust called the moon.

But though the modern cosmogonist thus changes the point of view, he does not greatly change the method of the Oriental dreamer. He, too, pushes beyond the boundaries of secure knowledge, and makes himself at home in the field of speculation. Indeed, it may fairly be said that much of contemporary astronomy, as judged by the most widely published findings of its proponents, is a metaphysico-poetic form of intellectual activity, rather than a rigidly inductive science.

The speculations of some of the leaders seem comparable rather to the cosmogonic dreams of the old Oriental poets than to the carefully documented hypotheses of the age of the astronomy of precision.

No Longer the Astronomy of Precision

Not three years of patient observation through a telescope such as Bessel gave to determining the parallax of 61 Cygni are requisite to establish a new thesis, but perhaps as many hours in the study, brooding over the figures of a laboratory worker who has measured star positions or relative luminosities on a photographic plate.

Yet the results are many times alluring. For the popular mind, these cosmogonic dreamings have an appeal that could never attach to mere logical inductions from prosaic measurements.

An Argelander devotes twenty years to testing the meridian positions of one star after another until the aggregate tests number hundreds of thousands. And when he has finished he has produced—a star-chart, showing the positions of a vast number of stellar bodies.

And this, for the average layman, has about the same interest

as a chart showing the location of a few thousands or hundreds of thousands of individual daisies in a meadow.

But the output of the laboratory dreamer is a product not of observation, but of imagination. It deals not with mere statistics of stars, but with the nature, the origin, the destinies of stars. And that brings at least into penumbral view the still more intimate questions of the nature, the origin, and the destiny of our own sun, of the earth on which we live, and by implication of man himself.

Hence the appeal of the type of poetic dreaming of the old Babylonian cosmogonists and of contemporary cosmogonists alike.

As we recalled the former at the beginning of this chapter, let us now turn to the very different but no less fascinating speculations of their twentieth century heritors.

A Symposial Scheme

It goes without saying that these up-to-date cosmogonic guesses have for foundation the entire structure of modern astronomical knowledge. They are put forward by way of interpretation of the observed phenomena of the celestial mechanism as recorded by full equipment of observatory and physical laboratory; and elaborated with the aid of mathematical equipment of the Einsteinian epoch.

It follows that the new cosmogony does not represent the speculations of any one man, but rather the symposial speculations of a whole coterie of astronomers. Yet, of course, certain spokesmen are the centers of attention—modern poets whose native medium is the mathematical formula, yet who also have the gift of tongues.

Among present day cosmogonists, none has envisaged the new cosmos more comprehensively than the distinguished mathe-

Genesis According to Jeans

matician, Sir James Jeans. How does he conceive the cosmic mechanism to have come into being; and what horoscope does he cast for its future?

Let us see.

At the outset, you must understand that Sir James, in common with many of his confrères, will tell you the formula that represents the relation between matter and energy, with the same manner of certitude with which he would speak of the mechanical equivalent of heat.

This is the contemporary view. You may find our own Doctors Mitchell and Abbot in a recent book saying that "matter seems to be a passive form of energy."

Or you may listen in a sort of dazed wonderment while Prof. Eddington says, quite casually:

"The stars lose mass by their radiation; there is no question about that. The sun is losing 120 billion tons [in England a billion means a million million] annually, whether its radiation comes from annihilation of matter or any other internal source."

That the source actually is annihilation of matter has been the favorite thesis of Sir James Jeans since he first put it forward as long ago as 1904,—one year before a theory of Einstein provided the means for calculating the amount of energy which would be produced by the annihilation of a given amount of matter.

Sir James spoke of "positive and negative electric charges rushing together, annihilating one another and setting their energy loose in space as radiation."

The formula of Einstein showed that energy is set free at the rate of 9×10^{20} ergs (that is, 900,000,000,000,000,000,000 ergs)

per gramme, regardless of the nature or condition of the substance which is annihilated.

As has been said, this thesis of the transmutability of matter into energy is an accepted doctrine of the mathematical astronomers of our times.

At all event, it is the basis of the calculations through which Sir James Jeans goes on to estimate the age of stars; to calculate the length of time since the stellar universe came into existence; similarly to calculate the probable future life-period of stars that have now reached the dwarf stage; and in general to exposit a doctrine of cosmogony, linked with the theories of stellar evolution that we have recently considered, which may be said to be the most comprehensive theory of the origin and destiny of the new heavens and the new earth that has hitherto been presented.

It is a thesis that harks back to Lockyer with his exposition of the dissociation of atoms, and the growth and decay of stars; in some of its features it follows closely the conception of Chamberlin and Moulton as to the origin of planetary systems; it is clearly reminiscent of the nebular hypothesis of Kant and Laplace as to its initial features. But as a whole it stands as an individual interpretation which we may summarize as representing the best cosmogonic guess that our generation can present for comparison with the cosmogonic guesses of tradition.

In the Beginning

Stated in the fewest words that will make it clearly intelligible, the new Scheme of Creation is this:

In the beginning, a vast rarefied nebula—"formless and void," if you care to hold to an old familiar phrasing.

Self-luminous as well, by virtue of the activities of its protons and electrons—wherefore there was light throughout the uni-

verse, though as yet there was neither sun nor moon, nor stars; quite as in that famous cosmogony of the Orient recorded in the first chapter of Genesis, where we read that light was created on the first day; and sun, moon and stars not until the fourth day.

But beyond that, the comparison no longer holds. The new cosmogony, except as to the mystery that enshrouds the very beginning of things, is in nowise reminiscent of the old.

The next stage of development is, however, reminiscent of Laplace, inasmuch as portions of the nebula begin to be segregated, under influence of gravitation, to become nascent stars. To show the extreme tenuity of the matter of the primal nebula, Jeans says:

"The small amount of gas in an ordinary electric light bulb, if spread out through St. Paul's Cathedral, would still be something like 10,000 times as dense as the nucleus of a spiral nebula."

(It will be understood, of course, that this interpretation of the nucleus of the spiral nebulae is purely speculative. No one knows for certain that these nuclei may not be as dense as a white dwarf star. Indeed, the results of spectroscopic tests which ascribe incredible speeds of retiring flights of these bodies, suggest that they may be far more dense than the dwarf-star—which, it will be recalled, has a ton of substance to the cubic inch. But to urge that point would be to substitute one speculation for another. Let us continue.)

As gravitation acts, pulling the particles of the new star closer together, while energy is radiated out in enormous quantities, representing corresponding destruction of mass of the star, the body necessarily shrinks, though growing progressively hotter quite as Lockyer and Russell conceived; until a point of equilib- Star-Growth

rium is reached, beyond which the star, still shrinking, becomes progressively cooler as well as smaller, passing on to an ultimate stage of complete exhaustion.

Some aggregations of the matter thus undergoing evolution may take on rotation, and assume the form of spiral nebulae. Double stars are also accounted for.

Other nebulae will remain spherical till they grow old and cold and solid, without ever becoming the parents of star systems.

But in the scheme of development as thus far outlined, Jeans sees no place for the production of a solar system.

The Planetesimal Theory Recalled

Yet at least one planetary system exists—as we know well, because we live on one of its minor members.

Probably there are many others in the universe, although there is as yet no direct evidence of their existence. Our own planetary system would be invisible from the nearest star, with instruments comparable to the best that we have developed, except that Jupiter might appear as the faintest possible companion of the sun and separated from his moderately brilliant point of light by the narrowest interval.

It could not be expected, therefore, that we should know of similar planetary systems, however abundant they might be in the stellar universe.

But how does the new theory account for the existence of the one planetary system of which we are certain?

Here the new theory is not merely reminiscent, but directively imitative. It adopts a suggestion made early in the century by Professors Chamberlin and Moulton, who in turn were doubtless led to the conception by consideration of a yet older thesis known as Roche's limit.

This is a thesis, it will be recalled, put forward in 1850 by

the French astronomer Roche, who calculated that if two stellar bodies, one larger than the other, were to pass by chance within a certain distance of each other; or if a small body were circling about a larger one, the smaller body would be disrupted by the gravitational pull if its orbit fell within 2.45 times the radius of the larger body.

In case the small body was of lower density than the larger, the critical distance is correspondingly increased.

Chamberlin and Moulton conceived that if two large bodies chance to hurtle near each other, not quite within Roche's limit, their mutual tidal influence might suck out an equatorial mass of matter, which would take on the characteristics of the arms of a spiral nebula. The spiral nebula thus developed became in the Chamberlin-Moulton view, the parent of future planetary systems.

The Rings of Saturn Explained

Jeans, as we have seen, explains the spiral nebulae without resort to such mutual influence, but he notes that the statistics of our planetary system, with reference to the relations between the planets and their moons, appear to confirm Roche's mathematical analysis.

He shows that all the prominent satellites lie well beyond the danger-limit; but notes that the inner ring of Saturn lies within that limit.

This suggests to him the correctness of the theory that Saturn's rings are the broken up fragments of a former satellite which ventured within the danger zone. He accepts, too, the theory that our own moon is destined in time to contract its orbit until it finally is drawn within Roche's limit, and broken into fragments.

After that, he says, the earth will have no moon but will be surrounded by rings like Saturn.

Looking back, he conceives that the substance of the sun, which now forms our planet, was originally tidal matter that was drawn out by the influence of another passing star, quite as Chamberlin and Moulton postulated.

Incidentally, shooting-stars are fragments of comets that were broken up because they chanced to pass the sun within Roche's limit—in accord with Dr. Olbers' famous theory.

In all this there is nothing novel. But as we stop to consider more in detail the condition of the sun itself, and of the various suns that make up the galactic system, there is opportunity for application of the new thesis of the transmutability of matter into energy, accompanied by startling calculations as to the time involved in the evolutionary processes, and an interesting forecast of future developments.

7,000,000,000,000 Years a "Convenient" Unit

We need not go into details. It suffices to note that estimates based on the observed rate of radiation of stellar bodies (with Einstein's formula to give interpretation in terms of annihilated matter) give 200 million million years as the upper limit of age for the present matter of the universe.

The age of our own sun is of the order of 7 million million years—a figure which has come to be spoken of as "a convenient cosmogonic unit of time."

If the sun is to devolve into a red dwarf of not one quarter of its present mass, no less than eighty cosmogonic units of time will be required for the process.

It gives one a feeling of unhurriedness to contemplate such figures.

Of their actual meaning, of course, the mind has no compre-

hension. At least they make strange contrast, however, with the slightly less than 6,000 years that represent the present age of the world according to Archbishop Usher's famous interpretation of the poetic record of the old cosmogony. (See the Bible margins of all but recent editions.)

What Will Be the End?

More interesting than the matter of time, however, is the question of ultimate destiny. *Why* a question to be settled billions of years in the future should be of interest, it might be hard to say. Yet it would be considered a very defective scheme of cosmogony that failed to consider the question. Sir James does not evade that problem.

His answer is emphatic and unequivocal: The destiny of the universe as a whole is the destiny of the matter that composes it—annihilation. Matter is transformed into energy, but energy is not transformed back into matter. And as the energy passes out into space, never to return, the universe is in the position of a machine that is running down and must ultimately stop. Destruction stares it in the face.

Here at the end the modern thesis might be said to be in accord with ancient prophecies, in which the destruction of the world so frequently figures.

On the other hand, we must recall that some of the ancient prophets, in foretelling the destruction of the old heavens and the old earth, foretold the coming of the new heavens and the new earth.

Theirs was a prophecy not of annihilation, but of destruction followed by rejuvenation.

It remains to be said that there are cosmogonic dreamers of today who would take issue with Sir James Jeans' conclusion,

aligning themselves—doubtless as to this matter only—rather with the ancient prophet than with the contemporary one.

Very briefly, we must note the foundations of this divergent speculation.

XXXV

THE MIRRORED UNIVERSE—AN ASTRONOMIC FANTASY

> Hast thou with him spread out the sky,
> which is strong, and as a molten looking glass?
> —*Oriental Anthology.*

THERE are two quite different lines of speculation according to either of which it may be possible that the universe is not facing annihilation, but is, on the other hand, a self-perpetuating mechanism.

The first is based on a suggestion of one of the greatest practical and speculative physicists of the 19th century, Lord Kelvin.

The other is an inference from one of the later assumptions of the hypothesis of Relativity.

According to either conception, the energy which passes through space may not be really lost to the universe, but conserved perpetually, and perhaps utilized—though that is no necessary part of either thesis—for the re-creation of the primordial substances, protons and electrons, that are the basis of the matter of which the present universe is constructed.

The Circumscribed Universe of Kelvin

The thesis of Kelvin was put forward not as a scientific induction, but as a cosmologic dream. This makes it none the less available for our present purpose.

The suggestion was merely this: For aught we know to the contrary, the universe in which we find ourselves may not be of unlimited extent. In particular, the hypothetical ether (which to that generation seemed to have as secure position as, let us say, relativity and the quantum hypotheses have for a large number of Kelvin's present-day successors) may come at the confines of our universe to a limiting surface, of whatever shape you may care to surmise, beyond which there is a medium of different character.

Should such be the case, we have every reason, from analogy, to suppose that the ether waves which we call radiant energy (quantum-shafts, if you prefer a newer terminology) will be reflected when they come to the new medium, somewhat as the same energy-carriers are reflected when in the course of their passage through air they come to a surface of an ordinary mirror.

In that event, the world-supply of energy, which on any other supposition hitherto presented seems to be largely rushing out in straight lines into space to pass beyond the confines of the universe forever, may in reality be confined within our portion of the universe, reflected back and forth in vast zig-zags across the galactic system (unless they chance to be intercepted by some stellar body or other medium) but forever confined to our world-system, by an impenetrable universe-shell.

The Curved Space of Einstein

Such a conception is alluring. It becomes the more alluring the more it is considered.

But before we glance at some of its implications, let us advance half a century in time to the other imaginative physicist, Ein-

stein, and consider one aspect of his theory of Relativity that singularly parallels the conception of a circumscribed universe just outlined, though reasoned from a quite different standpoint.

The particular aspect of that doctrine here in question is that which conceives that space itself is curved—curved in arcs that vary with the proximity of masses of matter, and with the total mass of matter. But curved so effectively, on the whole, that ether-waves (if you wish) or quantum-shafts of energy (if you prefer) pass through space in channels that in the long run prove to be curves, unless in an absolutely vacant universe.

The net result is, that the shafts of energy ultimately make full-circle, and come back to the place from which they started, somewhat as a comet returns to the sun; or as a planet sweeps round and round in the same orbit.

It follows, also, that the universe is of limited extent, in so far as it is a universe of matter and energy.

The circles of energy are not infinite in size, for there *is* matter in the universe.

In a word, we here encounter again the circumscribed—if you choose shell-bound—universe, criss-crossed and cob-webbed by flying shafts of energy, which can never escape from the galaxy in which they—and the stars and atoms and man—find themselves.

One recalls the Ptolemaic universe of epicycles.

Obviously the physically restricted universe of Kelvin and the mathematically restricted universe of Einstein are but different aspects of the same dream.

Let us now very briefly outline a few of the implications of the weird, fantastic, fascinating conception of a closed universe

which thus bottles up inescapably all the radiant energy that is ever generated within its confines.

A Mirrored Universe

The most familiar form of radiant energy is what we term light.

With every light-beam there are also associated heat-beams, which are merely entities of a different order of etherial wave-lengths or different size of quantum-arrow.

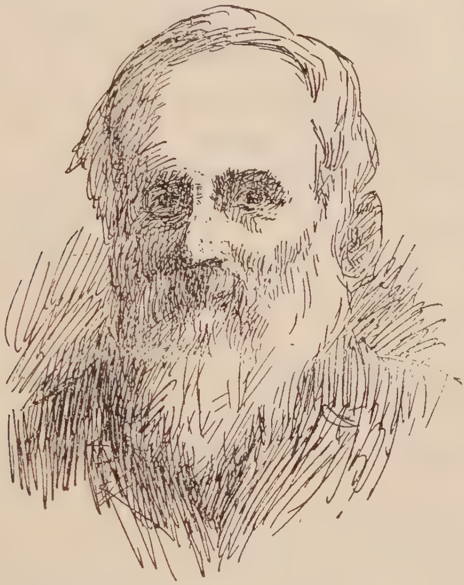


Fig. 99.—Lord Kelvin (1824-1907). (Crow-quilled from a half-tone in Williams' *Story of Nineteenth Century Science.*)

If, then, the Kelvin-Einstein concept is valid, all space must be shot full of light-beams and heat-beams, criss-crossing past the earth (and every other point in the stellar system), not merely as direct messengers from every light-giving body (nebula, star, comet), but also as reflected and re-reflected in infinite

series—precisely as rays of light are reflected and re-reflected in a closed room with mirrors for walls.

Perhaps you have seen this effect in an old-fashioned elevator with mirrors on three sides, or in a trick-room especially designed to show the phenomenon. You see your image a thousand times repeated in every direction.

So it would seem that a telescope—or for that matter the unaided eye—directed toward the heavens must receive an almost infinite series of images each of which appears to be a star—even though there were but a single actual star in the mirror-walled or curved-space-channeled universe.

Since we have reason to believe that there are scores, hundreds, even thousands of stars instead of merely one, the infinitude of images must be proportionately multiplied. Each one of the actual stars would appear of a certain brightness as directly envisaged, and as a progressive series of light-images of diminishing brightness, limited in number only by the limits of human vision, natural or aided by the light-gathering telescope.

Not all the endless series of fainter and fainter images would come from a single direction, of course.

Indeed, the most vivid of them might be expected to come from exactly the opposite direction, whether they come by direct reflection from the Kelvin mirror or circling through the curved-space orbit of Einstein.

The Same Nebulae in Opposite Directions

As an illustration, Sir James Jeans mentions that it has been suggested that a certain pair of nebulae to be seen in one direction of the heavens and a seemingly smaller pair of closely similar nebulae visible in the opposite direction are really the same pair of objects—that is to say, one pair of actual nebulae, and their Einsteinian image.

But to the eye of the telescope, the fainter pair of nebulae seem quite as real as the other—just as in a good mirror, the image of any object has convincing verisimilitude.

But where does this land us?

Why, obviously in a sidereal universe that is very largely a world, not of realities, but of mirror-pictures.

Nor would there appear to be any method whereby the observer can determine—or even clearly surmise—among a thousand or a million or a billion images of stars, what small modicum of images represent the actualities.

The only qualification would seem to be that exceedingly bright stars may be presumed to be originals, since reflected images grow ever fainter. But even this conclusion cannot be accepted quite without reserve; for might not the brightest of visible stars, Capella, for instance, be but the reflected image of our own sun—both of them being recognized as yellow stars of class G?

A surprising thought—yet after all no more surprising than many another concept associated with the new doctrine of Relativity, and put forward as verity by the devoted disciples of Einstein.

And let us not forget that, even were we to repudiate Einstein, there remains the mirror-coated universe of Kelvin to link Capella with the sun in quite the same fashion.

Do We See the Sun Mirrored as Many Stars?

It would follow, of course, that all the other multitudes of class G stars may be but secondary, tertiary, and so on images of the sun.

Minor variations of color and constitution (for, as we know, each major class of stars is sub-divided) might well be due to modifications of light-beams produced by passage through dif-

ferent strata of the vapor cloud of matter which, as we shall see in a moment, is by recent investigators demonstrated (or nearly demonstrated) to be distributed throughout interstellar space.

Perhaps it is only a coincidence, but in this connection it is worth noting that only about a score of stars are ranked as of "first magnitude," and that the number of major classes of stars (Draper classification) is curiously coincident.

Shall we assume that there may be only one, or at most a few, actual stars of each type in existence, and that all the myriads of seemingly more distant (because fainter) stars of the same types are but Kelvin-Einstein replicas?

Following up this fantasy, we shall be equally justified, no doubt, in assuming that the thousands of spiral nebulae are in reality only a handful—even only a single individual.

Shall we explain the curious similarity of ring nebulae, of globular clusters, of Cepheid Variables, of binary systems on the same mirage principle?

Shall we explain the galaxy—the myriad-starred Milky Way—as due merely to a chance curve of the reflecting mirror where many star-images and few actual stars are clustered?

Reality or Image?

Fantastic as such suggestions seem, there is a certain warrant for them in the observed locations of various clusters of stars and nebulae of individual forms.

Thus the globular clusters are curiously confined to a single quadrant of the heavens, symmetrically arranged on opposite sides of the Milky Way—quite as if most of them were reflected images sent to our eyes from the great parabolic Kelvin-mirror that lies back of the galaxy.

Then the two famous spectacles of the southern hemisphere, known as the Magellanic Clouds, are so placed—at approxi-

mately the same Declination (about 70 degrees) and with about sixty degrees difference in Right Ascension—as fairly to invite the inference that one is the image of the other. Incidentally, the inference here is that the small cloud is the verity, the large cloud being the enlarged image sent back by the big parabolic speculum.

The measurements which put the small cloud at 100,000 light-years and the large one at 110,000, suggest that the former (and only real) nebula is about 5000 light-years from the reflecting surface of the universe-shell, its reflected beams taking thus 10,000 light-years longer to get to us than the direct beams.

The case of the spiral nebulae is perhaps even more striking. To the number of somewhere between a hundred thousand and a million or more they appear to lie clustered at opposite poles of the watch-shaped galactic system—precisely as if there were really a score or so of them in actuality, endlessly mirrored and re-mirrored by the flattened parabolas of opposite sides of the galactic shell.

The first reflection would perhaps increase the seeming size of the nebula, but images sent back and forth many times before the earth interrupted them would be progressively fainter and, since the vast preponderance of the seeming thousands would be such re-reflected images, the spirals in general would seem to be very faint, as is the observed fact.

Reversed Direction of the Images

If the actual spirals were falling swiftly toward the observer (bound, say, for the gravitation center of the galactic system), the reflections would seem to be receding as swiftly. (Make a test for yourself in a mirror, and you will see the point.)

The fact that the two nearest spirals are registered by the spectroscope as *approaching* at high speed, while nearly all the

supposedly remoter ones (in the present view, minor images) are rapidly *receding,* is interestingly corroborative.

The excessive speeds credited to the spirals may be due, as already suggested, to the extreme density of their nuclei which, as in case of the white dwarf companion of Sirius, may cause a misleading shift of the Fraunhofer lines toward the red end of the spectrum.

We have already noted that were the companion of Sirius isolated in space, its spectrum would indicate movement away from the observer at the rate of nineteen miles per second, as a purely fictitious element added to whatever actual movement the star might have.

It has been pointed out, too, that no one has decisive evidence as to what is the nature of the heart of the spiral nebula. The conditions existing there, supplemented perhaps by the effect of outlying matter on the rays of light, may shift the Fraunhofer lines in a way to be utterly misleading. This explanation, indeed, seems far more plausible than to assume that the spirals are nearly all darting away from the galactic system, our universe, at speeds of from several hundred to one thousand or even two thousand miles per second. (Not that plausibilities are much in question in either case. And not that it really matters in the least which view, if either, is right.)

Of course such an interpretation of the line-shift would make necessary a revision of records of star movements hitherto considered valid. A new element of star density must, in this view, be considered in future computations, and in checking the old ones—somewhat as it was necessary to re-compute the positions of stars, and readjust star-charts when, back in the 18th century,

Halley discovered proper motion, and Bradley discovered aberration.

But this is an aside—though by no means of negligible interest. (Note, please, that I say "interest," not "importance.")

Are Star Distances Illusory?

Viewing the same phenomena from a slightly different angle, it is obvious that the conception of a mirrored universe introduces an altogether disconcerting thought about the inconceivably vast stellar distances of which the modern astronomers speak so casually—with basis of "light-years" and "parsecs."

If images are really mirrored—either by the Kelvin or the Einstein route—then it would appear that these distances are largely figments of the imagination.

Not that we can doubt that stellar distances are vast—ten light-years, if you will, or a hundred—but that measurements that take account of "100,000 light-years" or 100,000,000 (based as they are largely on the faintness of image of the object photographed) may represent measurement of countless zig-zag spannings of the universe by light-beams whose sister light-beams from the same source may come directly to us in a hundredth or a thousandth part of the time consumed by the detourant.

These are weird suggestions. But not unmeaning. If we accept the cogency of Lord Kelvin's suggestion, or—with a large group of the greatest mathematicians of our day—hold to the unassailability of the Einsteinian conception, there would seem to be no escape from envisagement of the mirrored universe as at least a semblance to be reckoned with until it can be proved a phantom.

Space Closing in on Itself

I have had in mind mostly the Kelvin shell rather than the curved space of Einstein—chiefly because the former seems to me less unplausible. But now a further word about the Einstein universe.

Sir James Jeans remarks that if we should ever see the world at the other end of the curved space in which light travels out from it, we shall see it as it was 500 million years ago.

But that is on the assumption that there is really (relatively) little matter in the universe. Now the trend of present investigation is to show (as will presently be noted more in detail) that there is matter everywhere in what was formerly thought of as empty space. Suppose we should find that there is really 5000 million times as much of this as had been estimated. Then the curved space of Einstein will, by hypothesis, curve in on itself in enormously contracted circles.

Let Professor Eddington tell the result. He is speaking of what Betelgeuse would be like if that great star were of the same mean density as our sun. It would then have, he tells us, these remarkable properties:

"First, owing to the great intensity of its gravitation, light would be unable to escape; and any rays shot out would fall back again to the star by their own weight.

"Secondly, the Einstein shift (used to test the density of the Companion of Sirius) would be so great that the spectrum would be shifted out of existence.

"Thirdly, mass produces a curvature of space, and in this case the curvature would be so great that space would close up round the star, leaving us outside—that is to say, *nowhere.*"

Seeing Earth-History Backward

This is the sober interpretation of one of the great champions of Relativity.

We may take it, then, as authoritative, that if there really should prove to be a vastly greater volume of matter in the galactic system than had been supposed, the rays of light will bend (in the view of the Einsteinian) so as to return to the

earth, not merely in 500 million years, but in a fraction of that time consonant with the amount of the matter hitherto not reckoned with.

Perhaps, then, the rays of light might bend back to us so that they would bring a record of earth-happenings not more than a few thousand, or tens of thousands, of years ago.

We are told that a 200-inch telescope is projected. Conceivably this might give us glimpses of wonders hitherto undreamed of—stranger sights even than those the spectroscope revealed.

Let us nurse that thought for a moment, along Einsteinian lines.

In three hundred years we have advanced from the two inch lens of Galileo to the projected 200-inch mirror—a hundred-fold increase. By the year 2200, then, should our successors advance in like proportion, there may be 10,000-inch mirrors that will show the past history of the earth year by year since living creatures first evolved.

After all, such a speculation is in keeping with the spirit of our Einsteinian age.

Is Energy Conserved in Our Universe?

Let us not hesitate to go farther along similar lines. There is another aspect of our main thesis, and indeed by far the most important aspect, yet to be considered, with reference to the Kelvin-Einstein concept of reflected or circling shafts of energy within a closed-system universe.

This is the salient question of the accumulation of energy within the galactic system—energy which, on the old assumption, passed off in straight lines into unknown regions beyond the universe.

Here is the import of the problem. All incandescent stellar bodies, from the giant Betelgeuse to the dwarf Companion of

Sirius, are giving off incessantly incomprehensively vast quantities of energy—representing, according to the modern conception, the transmuted substance of their bodies.

For trillions of years, according to Jeans' estimate, this flooding of space with energy has gone on without cessation.

Since all this energy is, on the present hypothesis, still present in the universe, why does not the whole firmament glow with light, as brilliant by night as the sunlight is by day? Why is there any limit to the number of images of the stars? Billions of such images there are, to the eye of the telescope, but why not billions of billions of billions?

It is estimated that if all the points of light of all the stars were brought together, as they appear to telescopic view, they would not cover a space as large as the apparent surface of the sun. This is a strange limitation, if there be no limit to the number of times that a star-beam may be reflected back and forth from the confines of the Kelvin-universe or circled about the structure of the Einstein corridors of curved space.

We should expect rather that all space, from whatever direction, would be aglow—that the firmament would be one glaring surface like a mosaic of suns.

How are we to explain the discrepancy?

For answer one might quote statistics by which the mathematicians—Sir James Jeans in particular—show how relatively insignificant is the supply of energy put forth by the stars, in relation to the vastness of the sidereal system.

But this is on the assumption that the energy passes off into space, and has all along been doing so since the beginning.

The case is quite altered if we consider the energy as still present and ever-accumulating within the sidereal system. On

that basis, it seems necessary to assume, either that energy is obstructed in its passage through inter-stellar space (which astrophysicists are inclined to deny) or else that part of the energy is annihilated or transformed into something different from what we term light and radiant heat, in which guise it leaves the stars.

Is Space Full of Matter?

As to the obstruction of light in its passing through inter-stellar space, a new question is raised by very recent investigations, to which incidental reference has been made, showing that there are "clouds" of matter, until recently quite unsuspected, diffused in space that has all along been thought of as totally empty.

Spectroscopic studies of Prof. Plaskett with the seventy-two-inch reflector at the Dominion Observatory in British Columbia have been so conclusive that Prof. Eddington is led to say that he thinks there can be no doubt of the existence of a "cosmic cloud" of ionized sodium, calcium, and probably many other elements unrevealed, pervading the stellar system.

"The fullness of inter-stellar space," he says, "becomes a point of observation and no longer a theoretical conjecture."

He even estimates the quantity of this matter in space, and reaches the conclusion that it is adequate to supply one atom, on the average, to every cubic inch of space throughout the sidereal system.

An ionized atom, it will be recalled, is one that has lost one or more electrons from its planetary system.

The presence of atoms thus stripped of their planetary constituents in otherwise vacant space is explained by Prof. Eddington on the assumption that beams of radiant energy in the depths of space, however spread out and however far from their source,

maintain unvaried their capacity to drive electrons from their orbit. The wide separation of the atoms in space greatly lessens the probability that the electrons will drop back again into their orbits.

Inter-stellar Matter Interferes with Light-Rays

But, however explained, the presence of inconceivable quantities of matter, in the aggregate, in what we have hitherto designated as "empty space" is a phenomenon with which the astronomer must reckon.

That this matter does interfere, in a measure, with the passage of light, is demonstrated in the fact that spectroscopic observation reveals its presence. The shaft of light that drives an electron from its orbit is no longer a shaft of light, but is, in effect, absorbed by the electron—only to be restored and sent on its way again as a shaft of light in case the electron drops back to its orbit.

So long as the electron remains a free wanderer in space, the shaft of light that liberated it is, as it were, stored in the electron's pocket.

If that sort of interference takes place often enough, the entire store of quantum-arrows of any particular star-beam must ultimately be intercepted and in effect annihilated.

Technically stated, their kinetic energy has been rendered potential.

But what becomes of the electrons that are thus liberated in space?

And what of the protons, their erstwhile mates, now widowed, back there in the nucleus of the deserted atom?

An ionized atom is a highly electrified, unbalanced structure. Failing to find electrons to restore the balance, it may conceivably adopt the alternative of ousting a proton or two from its

nucleus—becoming, in effect, a radioactive atom, under stress of circumstances.

Through this means, or any one of several others that might be conjectured, there may be free protons no less than free electrons abroad as components of the cosmic cloud of inter-stellar space.

Is Matter Created in "Empty" Space?

One might perhaps make an even more daring conjecture, and suggest that in the intricate meshes of commingling beams of radiant energy where the paths cross of light-messengers from myriad of sources (direct or reflected), whirlpools may be set up in the ether which, according to their magnitude or direction of twist, *become* primordial electrons or primordial protons—radiant energy being thus transmuted into the basic materials of "matter," even as aforetime in the heart of a star, the same radiant energy had been born of the destruction of other protons and electrons.

Thus would the conception of matter-energy-matter make full circle.

Such a conception of the veritable Creation of matter out of energy does not lie beyond the bounds of justifiable speculation, in the day when matter and energy may be gravely spoken of as probably different aspects of the same fundamental entity.

Without pressing that point, however, let us consider a little further the situation of the free protons and electrons just postulated as present in inter-stellar space—whether we conceive them to be created there or (what after all is not so very different) liberated there under influence of the beams of radiant energy that traverse the cosmic clouds.

liberated there under influence of the beams of radiant energy
and electrons.

The proton carries—or *is*—a unit charge of positive electricity; the electron, a unit charge of negative electricity. It is as inevitable that they should be drawn together, if they chance to come within a sphere of mutual influence, as that man should seek maid in the sphere of mundane affairs.

And when the mating occurs, an atom of hydrogen, the primordial element of what we term matter, is born.

The Birth of Cosmic Rays

When the electron swings into an orbit at a certain fixed distance from the proton, preparatory to whirling about in conventional manner, she will liberate the quantum of energy which she captured when driven from her former orbit or when rising from the ether whirlpool that was her cradle.

And this quantum of energy will start out on a new journey across the universe.

What next may happen is that two of the mated proton-electron pairs, called now a hydrogen atom, may combine to form a hydrogen molecule, and two of these molecules come together to form what we call an atom of helium.

And when this takes place there will go forth, as a kind of paean of rejoicing over the birth of the first complex atom, a veritable shower of quantum-arrows of energy to dart in all directions through space at the uniform-energy speed of 186,000 miles per second.

And it is these shafts of energy, if our interpretation is right—these witnesses of the creation of matter out in the vastness of inter-stellar space—that come to our earth, as (presumably) to every other body in the universe, with force so greatly in excess of the force of ordinary light beams that they can penetrate upward of twenty feet of lead.

These are the energy-messengers that Professor Robert An-

drew Millikan in particular has studied at his laboratory of physics in the California Institute of Technology, and to which the appropriate name of Cosmic rays has been given.

The peculiar quality of the rays—shorter wave-length even than X-ray and gamma-ray, with correspondingly greater penetrative power—leads Professor Millikan to believe that this recently discovered manifestation of energy can have no other origin than in some such creative synthesis in inter-stellar space as that just suggested.

Full Circle

Here, then, we have clear intimation of the creation of matter in inter-stellar space, to form the basis of the nebular-clouds which from Kant to Jeans—not to include the Oriental dreamers—have been postulated as the initial structureless structure—"formless and void"—out of which the world-systems have evolved.

And we may assume that, say, 200 million million years after their creation day, these atoms will meet their ultimate fate in the heart of a star, to be transmuted back into a shaft of radiant energy precisely like the one that was responsible for bringing them into existence.

Such, then, is the full circle of the scheme of Creation and destruction—of life and death—of the cosmic bodies, as the newest conceptions and interpretations of astronomical and physical science enable us to envisage and interpret it.

It is an awesome formula.

A tentative formula at best, revealing the mere outline of a picture.

Would that some poet might come, dowered with the gift of tongues, as the poet who enshrined in words the story of the old heavens and the old earth was dowered, to immortalize (even if

only as an historic landmark) the 20th century conception of the new heavens and the new earth.

In default of that, it is open to each of us to go out on to the nearest hilltop at night, and gaze up at the firmament, and with the factual basis of present-day astronomy for mental background, dream our own cosmologic and cosmogonic dreams.

I commend that inspiring pastime to every reader of these pages. It will be found a spirit-lifting, soul-clarifying experience.

APPENDIX

A

A FEW WORDS ABOUT ASTRONOMY BOOKS

I FIRST became familiar with the original sources of astronomical history when writing the early chapters of my *Story of Nineteenth Century Science* more than thirty years ago. The earlier sources were investigated in the preparation of *A History of Science* (in which I had the valued assistance of my brother, Dr. Edward Huntington Williams) which appeared in a first edition of five volumes, in 1904. Many of the original source-documents of astronomical history are quoted in that work, and a rather full bibliography of sources and earlier works may be found in the appendix to volume five.

Any reader who is likely to be in position to follow up the sources, or is inclined to do so, will probably be able to consult the work in question, which appeared in a second edition, expanded to include the mechanical arts, in eleven volumes, in 1909.

Both editions of *The History of Science* are now out of print, but they may be consulted in libraries, and will be found to present a much fuller account of the early astronomical development, in particular, than is given in the present book. The plan of the present work permits only occasional and brief excerpts from the source-documents that were freely drawn on in the eleven-volume work.

In a book called *Miracles of Science* (1914), and in my ten-volume *Story of Modern Science* (1923) I have presented somewhat in detail certain aspects of modern astronomical devel-

opment. Most of the topics treated in either book are dealt with in detail in the present book, from a slightly different angle (for of course the viewpoint of a science changes decade by decade), but, although the present treatment is entirely new, the changes are not fundamental, and the astronomical chapters of the *Story of Modern Science* in particular are by no means superseded. There are of course auxiliary aspects of science in the ten-volume work that might furnish supplementary reading—and nowadays there is very close interdependence between astronomy and the other physical sciences.

It would be superfluous to introduce here a general bibliography of astronomical books or writings, since anyone who is in position to consult the extensive literature of astronomy can use the library catalogues in which the works are found, and a good part of the more important ones can be secured at the bookstore. I wish, however, to name a few very recent works, each admirable of its kind, which I would commend to the attention of any reader who cares to extend his knowledge of astronomy—as I hope many readers will be disposed to do.

Of course there are many other more or less recent books on astronomy. I shall here mention only a few that I have myself consulted constantly in writing the later chapters of this book, and which I wish especially to commend.

Here are two recent books of the textbook order, comprehensive, condensed, yet exceedingly readable:

The Elements of Astronomy. A non-mathematical textbook for use as an introduction to the subject in colleges, universities, etc., and for the general reader. By Edward Arthur Fath, Professor of Astronomy in Carleton College. Second Edition 1928, McGraw-Hill Book Company, Inc.

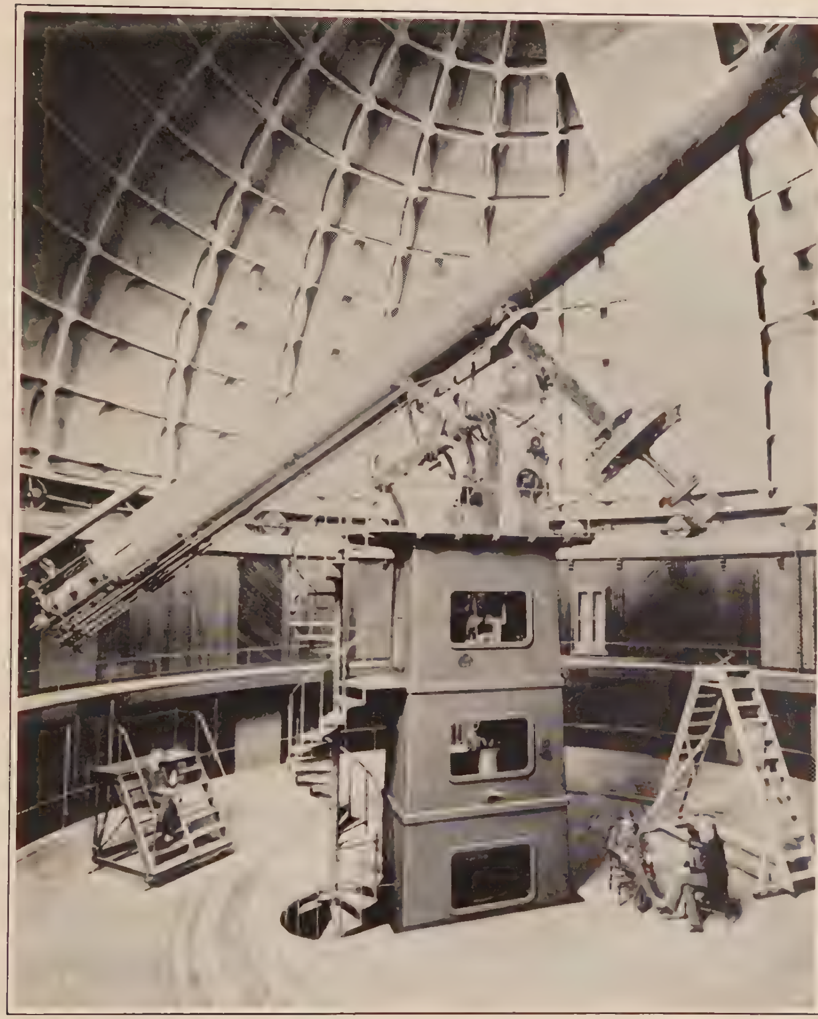


Plate XXII: The 36-inch Refractor of Lick Observatory

The Fundamentals of Astronomy. By S. A. Mitchell, Ph.D, LL.D. Director of the Leander McCormick Observatory, and C. G. Abbot, M.S., D.Sc. Director of the Astrophysical Observatory. D. Van Nostrand Co., Inc. 1928.

The following are books of popular character, in the best sense of the word: highly authoritative narrative treatments of various aspects of recent astronomical development.

The Earth and the Stars. By Charles G. Abbot (a good deal of the matter in this book is reproduced in "Fundamentals of Astronomy," above mentioned, of which Dr. Abbot is joint author). Fully illustrated. D. Van Nostrand Co. 1927.

The Sun, The Stars and the Universe. By W. M. Smart, M.A., D.Sc., F.R.A.S. John Couch Adams, Astronomer and Chief Assistant in the University Observatory, Cambridge. Longmans, Green & Co. 1928.

Meticulous in specifically crediting discoveries; sometimes verging on the technical in elucidation of astronomical methods; always of interest to anyone who cares to give reasonably close attention; very fully illustrated, with photographs, diagrams, and tables.

Two books on the constellations: practical guides to the open-air study of the stars.

A Guide to the Constellations. By Samuel G. Barton, Ph.D. Assistant Prof. of Astronomy, University of Penn., and Wm. H. Barton, Jr., C.E., M.S., Assistant Prof. of Highway Engineering, University of Penn., McGraw-Hill Book Co., Inc., 1928.

A large star-chart for each month of the year with full interpretations, and a wealth of interesting information about individual constellations and stars. The large size of the charts makes

them of peculiar value, and the admirable typographical arrangement of the text makes all information readily accessible. Anyone who uses this book as a guide, may readily gain a very comprehensive knowledge of the visible heavens.

Astronomy With an Opera-Glass. By Garrett P. Serviss, D. Appleton & Company. 1928.

A highly practical guide to the stars, with the information presented in narrative style. The charts are smaller, each giving a view of a small portion of the heavens, and the book is therefore better adapted for use of one who has a general knowledge of the constellations. It contains also a chapter on the moon, the planets, and the sun.

Our text refers very often to two outstanding mathematical astronomers, each of whom writes delightfully about astronomical matters in general, and in particular about the more speculative aspects of the subject of physical conditions in the sun and stars and moot points of cosmogony that are now so much in evidence. I refer, of course, to Professor A. S. Eddington and Sir James Jeans.

The Universe Around Us. By Sir James Jeans, M.A., D.Sc., LL.D., F.R.S. The Macmillan Company, 1929.

Stars and Atoms. By A. S. Eddington, M.A., D.Sc., LL.D., F.R.S., Plumian Professor of Astronomy in the University of Cambridge. New Haven: Yale University Press, 1927.

No one who is interested in present day problems of astronomy can afford to miss either of these books. Professor Eddington's still more recent book, *The Nature of the Physical World* (1929) is no less delightful, but demands fairly close attention on the

part of the reader, as it deals with subjects which, in the hands of a less poetically minded technician, might readily take the non-technical reader beyond his depth.

The reader who "intends" his mind receptively, will find these books of Sir James Jeans and Professor Eddington quite literally "more fascinating than novels."

If your interest in astronomy is such that you would like to go to the sources, and learn just what the great astronomers said in announcing their discoveries, you can now gratify this ambition without going to a library, for the source documents from Copernicus to the close of the 19th century have been gathered into an indispensable reference book under title of:

A Source Book in Astronomy. By Harlow Shapley, Ph.D., LL.D., Professor of Astronomy in Harvard University and Director of the Harvard Observatory, and Helen E. Howarth, A.B., A.M., Research Assistant at the Harvard Observatory. McGraw-Hill Book Co., Inc. 1929.

Additional value is given the book by brief critical biographies of each of the great astronomical discoverers whose original announcements are presented.

Men who make great discoveries can usually transmit something of their enthusiasm to the written word. Nearly all these papers will be found intrinsically interesting, even aside from their historical significance. This source book is of course absolutely indispensable to every serious student of astronomy.

B

ALPHABETICAL SUMMARY OF ASTRONOMICAL SUBJECTS

Aberration of lenses is due to the fact that the rays of light are not all brought to the same focus by an ordinary lens. The rays from the outer part of the lens tend to a shorter focus than those nearer the center, thus causing a spherical aberration. The lens tend to split the light-beam into a spectrum with the red waves of longer focus than the violet, thus causing a colored image. This is chromatic aberration. Correction is made by com-

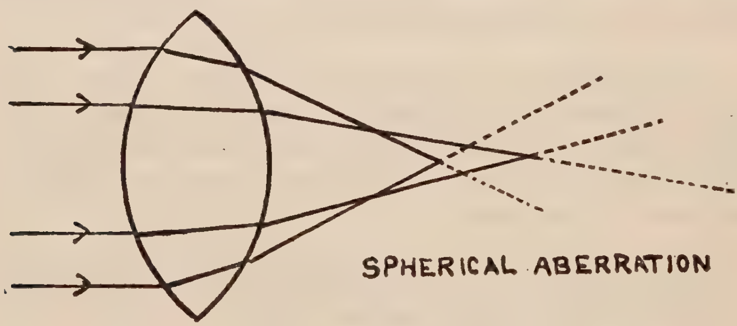


FIG. 100.—The Rays of Light Passing Through a Homogeneous Lens Are Not Brought to One Focus.

bining flint glass and crown glass lenses, and by modifying the curve of the lens. The reflecting telescope using a curved mirror instead of lenses, brings the light to a better focus, with comparatively little spherical aberration and no chromatic aberration. The surface of the mirror must be parabolic, not spherical.

Aberration of light causes the apparent displacement of stars and planets, viewed through the telescope, because of the earth's motion and the fact that the speed of light is not infinite. The discovery of aberration was announced by James Bradley in 1728.

The amount of apparent movement of the star is too small to be observed with the naked eye. Yet it amounts to more than 20 seconds of arc, a very significant telescopic distance. Polar stars appear to describe a circle; stars of intermediate portions of the heavens, an ellipse; and stars at the ecliptic swing back and forth in the same line. A correction for aberration must be made in case of all accurate astronomical observations that have to do with the placement of stars or planets. The so-called "constant" of aberration, used in making a correction, is 20.47 seconds, with a possible error of 0.01 or 0.02 seconds.

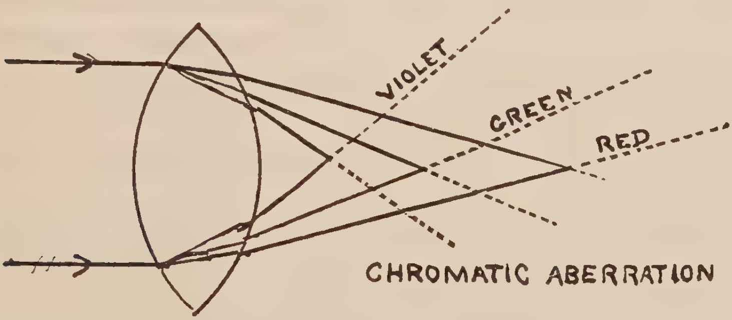


FIG. 101.—A Lens Acts as a Prism and Disperses Rays of White Light, Bringing the Colors to Different Foci.

Aerolite. A name sometimes applied to the objects more commonly known as meteors or shooting stars. Millions of such objects fall into the earth's atmosphere every day. They are probably fragments of "world-stuff" comparable to the matter making up the bodies of comets—and may even represent the dismembered fragments of comets.

Albedo of a planet. Its reflecting power, representing the fraction of the sun's light which it reflects. Thus the albedo of Mercury is only 7 percent, while that of Venus is 59 percent (that

of white paper being 70 percent). The mean albedo of Mars is about 15 percent, but different determinations vary. The mean albedo of Jupiter is 56 percent, of Saturn 63 percent, of Uranus 63, of Neptune 73 percent. Neptune has a stellar magnitude of 8, and is therefore never visible to the naked eye. Uranus may be seen as a star of the sixth magnitude under favorable conditions, but is usually invisible. Saturn appears always as a bright star, varying from magnitude 0 to 1.5. Jupiter at brightest is far brighter than any star, having magnitude *minus* 2.3. At conjunction the magnitude falls to *minus* 1.5. Only Venus exceeds Jupiter in brightness as a rule, though Mars at close opposition may outshine it for a short time. The asteroids are telescopic objects, mostly too small to be measured. The largest is slightly less than 500 miles in diameter the smallest probably not more than 3 or 4 miles. Mars varies from *minus* 2.7, a greater brightness than that of any other planet except Venus, to plus 2.0—the appearance of a second magnitude star. This great variation in the appearance of Mars is said to have been one of the things that led Copernicus to reflect on the unplausibility of the old geocentric or Ptolemaic system. The stellar magnitude of Venus varies from *minus* 4.4 downward. Venus shows phases like the moon, and therefore at times is only a sickle of light. At brightest, Venus may be seen with the naked eye in full daylight. Stars may be seen in daylight only with the telescope. Mercury is difficult to see, owing to its nearness to the sun. At its brightest it appears as a very large first magnitude star of scale *minus* 1.9. (For explanation of the scale of magnitudes, see *star-magnitudes*.)

Aphelion of a planet. The point of the orbit at farthest distance from the sun (opposed the perihelion, the nearest distance). The

earth is at aphelion at the summer solstice, about June 21st. As at that time the axis is tipped toward the sun, the northern hemisphere has summer, so the heat received is somewhat less than that received by the southern hemisphere during its summer season, when the earth is at perihelion. Contrariwise, the northern-hemisphere winter is slightly less severe because the earth is nearer the sun than during the southern-hemisphere winter. This accounts, in part at least, for the greater severity of the Antarctic winter. Possibly the (probably) earlier development of life in the southern hemisphere may have been associated with the occurrence of southern summer at perihelion.

Apogee of the moon. The moon's farthest distance from the earth—corresponding to the aphelion of a planet. The opposite of apogee is perigee, corresponding to perihelion. The eccentricity of the elliptical orbit of the moon is 0.055. The plane of the orbit is inclined to the plane of the ecliptic at an average angle of 5 degrees 9 minutes. This is added to or subtracted from the earth's inclination at about 23½ degrees, accounting for the familiar fact that the moon sometimes rises very high in the sky, and sometimes circles very low. The average angular diameter of the moon is a little over 31 minutes, or slightly more than half a degree. This gives a convenient gauge for estimating apparent distances between stars—one degree being slightly less than twice the apparent diameter of the moon.

Apsides. The line of apsides is the line of the long diameter or major axis of an ellipse. This imaginary line rotates, though the ellipse itself maintains its shape unchanged. The changing position must of course be taken into account in calculating the orbits of planets and the moon. The swing of the apsides is due to the

mutually disturbing influence of the planetary bodies, through gravitation.

Arc of a circle or ellipse or other curve. Any portion of the curve, measured by the angle it subtends from the center of revolution—which in case of the planets is the sun's position at the major focus of the ellipse, for purposes of calculation of the orbit; or the position of the human observer on the earth, as in case of a navigator. For purposes of the ordinary observer, the elliptical orbit may be regarded as circular, and the arc measured is usually that described by the sun or a star in a given period. Since every circle is divided into 360 degrees, a quarter-circle, or the distance from horizon to zenith, is 90 degrees. The arc of the altitude of the pole star above the horizon, measured in degrees, represents the degree of latitude of the place where the observation was made (with slight correction for the pole star's distance of something more than 1 degree from the actual pole). The simplest arc to measure is that of the sun's distance from the zenith when on the meridian, as shown by the shadow cast by vertical post, or, roughly, by the shadow cast across the face of a watch held with its edge toward the sun. The distance between the hour-marks on the face of the watch, measured from the center, represent 30 degrees (one 12th of the circle). On the day of either the vernal equinox, March 21, or the autumnal equinox, September 23, the sun being directly over the equator, its apparent angular distance from the zenith when on the meridian represents the latitude of the place where the observation is made, It was through such an observation that Eratosthenes first measured the size of the earth—except that his observation was made on the day of the solstice, at a known distance from the tropic of cancer. Such an observation serves the purpose equally

well, but in that case of course the distance of the tropic of cancer from the equator (ca. 23½ degrees) must be added to the angular distance of the sun from the zenith to give the latitude.

Asteroid. A minor planet, otherwise called a planetoid. There are hundreds of these bodies in the otherwise vacant orbit between Mars and Jupiter.

Astrolabe. The ancient forerunner of the modern sextant, for measuring the altitude of heavenly bodies. A watch used in the manner described in the preceding paragraph, is, in effect, an astrolabe. Like the original astrolabe, it determines the vertical by being suspended like a plumb-line, and the minute hand may be adjusted to point directly to the sun, like the similar revolving arm of the astrolabe. The watch will serve also for measuring the altitude of the moon, but of course it would be useless for observation of a star. A crude astrolabe for roughly measuring the altitude of stars may be made with two crossed sticks, one weighted to hang in the vertical direction, the other being sighted at the star. A transit telescope is merely a highly developed apparatus to serve the same purpose with accuracy.

Azimuth of a heavenly body. The angular distance of the sun or a star or planet representing its apparent position above the horizon, measured westward from the point directly south of the observer. Combined with a measurement for altitude this gives the apparent position of a star at the moment of observation. The actual position of the star as regards right ascension and declination is more accurately measured as the star crosses the meridian, the instrument commonly used being a meridian circle, so mounted that it can be rotated to aim high or low, but never departs from the meridian. An instrument mounted to swing

about horizontally as well as on the vertical axis, like a surveyor's transit, is called an altazimuth telescope. Such an instrument has a wider field of usefulness, but lacks the extreme accuracy of the meridian circle, owing to the flexible mounting.

Base line. The line carefully measured by the surveyor for use in "triangulating" a territory. The importance of the base line makes it necessary to use extreme care in determining its precise length. One method of measurement is to use rods encased in ice, to prevent variation through change of temperature. Another is to use a special metal alloy, called "invar" (short for "invariable") a metal that changes very slightly with ordinary modifications of temperature. The astronomer's base line for measuring solar distances is the semi-diameter of the earth itself. For stellar distances, the distance of the sun from the earth is the unit. The actual astronomical base line used in determining the distance of a star by the trigonometric method is the diameter of the earth's orbit.

Binary star, or binary system. A synonym for "double star." The existence of pairs of stars, linked by gravitation, is the rule rather than the exception in the stellar system. Many of these doubles are separated by enormous distances, though the vastly greater distance that separates them from the earth may make them appear to naked-eye observation like single stars. One test of a telescope is its capacity to separate doubles. The spectroscope reveals thousands of stars as binaries that are not separated even by the magnification of the largest telescope. Thus binaries are spoken of as visual, telescopic, or spectroscopic. Variable stars of one type (of which Algol is a conspicuous example) owe their variability to partial or entire eclipse of one mem-

ber of the double system by the other, as they revolve about a common center.

Bolometer. An exceedingly sensitive electrical thermometer used to measure the heat of rays of minute intensity. Invented by Samuel P. Langley, of the Smithsonian Institution, and used effectively also by his successor, Dr. Charles G. Abbot, in testing not only minute variations in the sun's heat, but also the heat of some individual stars and planets.

Cassegrainian telescope. A reflecting telescope, invented by Guillaume Cassegrain, a sculptor in the service of Louis XV, modeler and founder of many statues. His reflecting telescope differs from the Newtonian in that it has a convex lens in the interior of the tube, which reflects the rays back through a hole in the center of the mirror, so that it can be used after the manner of a refracting telescope. It may be variously modified, so that the reflected rays come to the side of the tube. The Newtonian telescope had a reflecting mirror near the mouth of the tube, which sent the rays to an aperture in the side of the tube. Herschel, who developed the reflecting telescope, preferred to stand at the mouth of the tube, and receive the rays directly into the object glass at his eye, thus avoiding loss by second reflection. The Cassegrain and Newtonian telescopes were invented in the same period, but they hardly competed with the refracting telescope until the time of Herschel.

Chronograph, an electrical clock attachment, consisting of a revolving cylinder, covered with paper, having a pen-point resting on it, so that as the cylinder revolves the pen leaves a trace on the paper. An electric button is pressed by the observer at the telescope at the moment when a star under observation comes to the spider-web at the centre of his field. This causes the pen

to make a notch in the tracing, and thus makes a permanent record of the time of transit of the star. There is a slight difference in records made by different observers, owing to the "personal equation," representing a difference in the reaction time of different individuals.

Chronometer. A watch of high precision used chiefly to determine longitude at sea. The lack of such an instrument made early navigation difficult, and it was only after the development of chronometers, with compensating balance wheels, that longitudes could be accurately determined. At best, the determination of longitudes by the chronometer does not equal in accuracy determination made by telegraphic or cable communication, or in modern times by radio. Since no chronometer is absolutely accurate, it is usual for a ship to carry three, taking the mean time. If, however, the rate of gain or loss of a given chronometer is known, the exact time can of course be accurately computed from it.

Circle, great. A great circle is defined as any circle which includes the two ends of a single diameter of a sphere. That is to say, it is a circumference of a plane that cuts the center of the sphere. The equator is a great circle, but no other *parallel* on the globe is, technically, other than a "small" circle, even though it may be a single degree or less from the equator. All *meridians* are great circles. The technical use of the terms is sometimes confusing, since the astronomer may speak of a "small" circle in referring to an arc of the sky of practically infinite extent, while referring to the meridian or equator of a small planet as a "great" circle. The distance along the arc of a great circle, in the technical sense, gives the shortest distance on the globe between any two points lying on that circle. Thus the anomaly appears that

if two places lie precisely on the same parallel of latitude, and therefore directly on the east and west lines, the shortest distance between them is not this east and west line, but a line curving slightly along the arc of the great circle which would include the two places and the center of the earth in one plane.

Coelostat. An instrument for producing a fixed beam from a celestial object usually the sun. It has a plane mirror parallel to the earth's axis, and rotates about an axis parallel to that of the earth, at a rate of one revolution in 48 hours. Often a second mirror is employed to send the fixed beam in a desired direction. The coelostat is advantageous for simplicity, and for preserving a non-rotating field of view (Abbot).

Conjunction. Said of two celestial objects when they have the same longitude or right ascension. When the earth is in direct line between the sun and Mars, or any other outer planet, the earth and the outer planet are said to be in opposition. Mercury and Venus are in conjunction when they pass directly between the earth and the sun. Conjunction of an inferior planet is inferior or superior according to whether the planet is on the same side or on the opposite side of the sun from the earth.

Constellations. The imaginary outlines that divide the sky into "constellations" are an unfortunate heritage from remote antiquity. The Greeks got the idea of them from the Egyptians, and perhaps more or less remodeled them, substituting their own heroes and mythological figures for Oriental ones. As the constellation figures were modeled to include the conspicuous stars, they served a purpose, and the mythological associations no doubt added interest. But the modern astronomer finds them exceedingly inconvenient, and he has substituted expanded outlines to cover the entire sky, filling in interstices with small constellations wher-

ever necessary. Of course, the ancients did not know the southern constellations that lay below their horizon, so new names and figures were given these when exploration made them known. It would be a great convenience if the old irregular lines could be swept away, and meridians and parallels substituted. But it is unlikely that this will be done, owing to the great confusion that would result in referring to old catalogues. Yet for purposes of the great photographic star-charts, this method does, in effect, prevail. There are of course untold millions of stars that have no names and that would be referred to in terms of right ascension and declination without thought of the particular constellation or constellations in which they chanced to fall. Here is a complete alphabetical list of about 90 constellations: 28 northern, 12 zodiacal (making a belt around the ecliptic), and about 50 southern (one or two southern ones have been divided on some modern charts: so the total number varies by three or four in different lists). The prominent constellations visible in the northern hemisphere may be located on the map (see "Charts of the Constellations" Appendix C) and those that contain the first-magnitude stars visible in northern latitudes are arranged in a table given below (cf. "Magnitude"):

List of Constellations

northern (28)

Andromeda, Aquila (Eagle), Auriga (Charioteer), Boötes, Camelopardalis (Giraffe), Canes Venatici (Hunting dogs), Cassiopeia, Cepheus, Coma Berenices (Berenice's hair), Corona Borealis (Northern crown), Cygnus (Swan), Delphinus (Dolphin), Draco (Dragon), Equuleus (Colt), Hercules, Lacerta (Lizard),

Leo Minor (Smaller lion), Lynx, Lyra (Lyre), Ophiuchus or Serpentarius (Serpent bearer), Pegasus, Perseus, Sagitta (Arrow), Serpens (Serpent), Triangulum (triangle), Ursa Major (Great bear), Ursa Minor (Lesser bear), Vulpecula (Little fox).

ZODIACAL (12)

Aquarius (Water Carrier), Aries (Ram), Cancer (Crab), Capricornus (Horned goat), Gemini (Twins), Leo (Lion), Libra (Balance), Pisces (Fishes), Sagittarius (Archer), Scorpius (Scorpion), Taurus (Bull), Virgo (Virgin).

SOUTHERN (50)

Antlia (Air pump), Apus (Bird of paradise), Caelum (Graver), Canis Major (Larger dog), Canis Minor (Smaller dog), Carina (Keel), Centaurus (Centaur), Cetus (Whale), Chameleon, Circinus (Compass), Columba Noachi (Dove), Corona Australis (Southern crown), Corvus (Crow), Crater (Cup), Crux (Cross), Dorado (Gold-fish), Eridanus (Eridanus, a river), Fornax (Furnace), Grus (Crane), Horologium (Clock), Hydra (Sea serpent), Hydrus (Water snake), Indus (Indian), Lepus (Hare), Lupus (Wolf), Mons Mensa (Table Mountain), Microscopium (Microscope), Monoceros (Unicorn), Musca Australis (Fly), Norma (Level), Octans (Octant), Orion, Pavo (Peacock), Phoenix, Pictor (Easel), Piscis Austrinus (Southern fish), Puppis (Stern of a ship), Pyxis (Compass), Recticulum (Net), Sculptor (Sculptor's work-shop), Scutum (shield), Sextans (Sextant), Telescopium, Tucana (Toucan), Triangulum Australe (Southern triangle), Vela (Sails), Volans (Flying fish).

Culmination. The passage of a heavenly body across the meridian. Stars near the pole, which seem to make a complete circuit of

the heavens are in lower culmination when below and in upper culmination when above the altitude of the pole.

Day. The period of about 24 hours might seem to require no definition. But astronomically there are three kinds of days. The solar day represents the time required by the actual sun to pass from meridian to meridian. The mean solar day, which is the practical day of common life, is the average or mean time required by the sun to pass from meridian to meridian, which varies by several seconds from day to day and cumulatively, so that sometimes the standard clock (and the fictitious sun) are 15 or 16 minutes away from the actual sun. The sidereal day is the time interval between the successive crossings of the meridian by any single star. This does not vary because the stars are so distant. The astronomical clock is set for sidereal time.

Declination. The distance, measured in degrees, of a celestial object north or south of the celestial equator. Declination therefore corresponds to latitude on the earth's surface. The meridional position corresponding to longitude is called Right Ascension.

Double Star. Close companion stars, which may or may not be physically associated. If known to be thus associated, and therefore in revolution about a common center, double stars are technically spoken of as binary systems. Binaries may be visual or spectroscopic. In the latter case, they are too close to be separated by the telescope, but the double character is revealed by the shaft of the Fraunhofer lines in the spectrum.

Durchmusterung. A star chart, in particular the great *Bonner Durchmusterung* of the astronomer Argelander, which gives place and brightness of over 324,000 stars, including all in the northern heavens to the ninth magnitude.

Ecliptic. The path in which the earth revolves about the sun.

The plane of the ecliptic is the plane passing through this orbit and through the center of the sun extended indefinitely. Owing to the practically infinite distance of the stars, the intersection of this plane with the celestial vault may be regarded as fixed. This is true also of the celestial equator, which is the extended plane of the earth's equator. The line of intersection of the two planes slowly shifts, however, constituting the precession of the equinoxes, the reason being that the axis of the earth, though commonly spoken of as absolutely fixed, is in reality swinging very slowly about in a circle, as the axis of a spinning top swings, without changing appreciably the angle between the planes of ecliptic and equator—except by the exceedingly small wavy motions known as nutation, which has a period of more than 18 years.

Ephemeris. A table of positions of celestial objects at successive times. The American Ephemeris and Nautical Almanac, issued year by year by the government, and prepared by the superintendent of the U. S. Naval Observatory and the Astronomical Council, is a bewildering array of figures, for the use of navigators, but has interest for the amateur observer who may wish to locate the sun or any particular stars from day to day. Anyone who wishes to study sun-shadows, or "zenith-angles," in the way suggested in another section of this Appendix, may advantageously have at hand a copy of the Nautical Almanac, to locate the sun's latitude exactly.

Eras or epochs. An interesting list of some of the more important eras is given in the Nautical Almanac. One of the most widely recognized chronological eras is that of the Julian calendar. January 1, 1930, of the Julian calendar corresponds to January 14,

1930, of the Gregorian calendar. The Julian day-number of January 1, 1930, of the Gregorian calendar is 2,425,978.

Equinox. The instant when the sun occupies the line in the heavens which is the intersection of the plane of the equator with the plane of the ecliptic. On the day when this occurs, day and night are equal everywhere on the globe. The vernal equinox occurs about the 21st of March, and the autumnal equinox about

FIG. 102.—Foucault Pendulum. (Explained in the text.)

the 23rd of September. There is a variation of a few hours, owing to the fact that the earth's revolution about the sun does not take place in an exact or even number of days. The equinoxes do not precisely bisect the year; because of the ellipticity of the earth's orbit the winter "half" of the year is shorter.

Foucault pendulum. A very long pendulum devised by the French physicist Foucault, to demonstrate the rotation of the

earth on its axis. The pendulum is set swinging, suspended from the dome or ceiling of a high room, and it continues to swing in the same plane, while the position of the earth shifts under it. The changing relations of the swinging pendulum and objects in the room demonstrate the earth's rotational movement. Foucault made a similar demonstration with a gyroscope in gimbal rings.

Galactic latitude. The angular distance of a celestial object from the medium plane of the Milky Way—a plane chosen somewhat arbitrarily, but the general direction of which is unmistakable.

Galaxy. Originally meaning the Milky Way. The word is now applied not only to our system of stars, but to nebulae that are supposed to represent outlying systems.

Gravitation. Says Simon Newcomb: "No work of the human intellect farther transcends what would seem possible to the ordinary thinker than the mathematical demonstrations of the motions of the heavenly bodies under the influence of their mutual gravitation. We have learned something of the orbits of the planets round the sun; but the following of the orbit is not the fundamental law of the planet's motion; the latter is determined by gravitation alone. This law, as stated by Newton, is so comprehensive that nothing can be added. The law that every particle of matter in the universe attracts every other particle, with a force which varies inversely as the square of the distance between them, is the only law of nature which, so far as we know, is absolutely universal and invariable in its action. All the other processes of nature are in some way varied or modified by heat and cold, by time or place, by the presence or absence of other bodies. But no operation that man has ever been able to perform on matter changes its gravitation in the slightest. Two bodies gravi-

tate by exactly the same amount, no matter what we do with them, no matter what obstacles we interpose between them, no matter how fast they move. All other natural forces admit of being investigated, but gravitation does not." Contrary to a popular conception, the Einsteinian hypothesis of relativity does not profess to modify the Newtonian law, except by an infinitesimal amount under conditions not claimed to be observable except in two instances amidst all the phenomena of the planetary and celestial mechanisms. In other words, for every practical purpose, Newtonian gravitation and Einsteinian gravitation are absolutely identical. In the words of Professor Charles Lane Poor, the difference between them is expressed succinctly in two words—"No difference!"

Heliocentric. Having the sun at the centre. The doctrine of Copernicus is the heliocentric conception of the planetary system, in contradistinction to the geocentric, or earth-centred conception, which had been universally accepted by mankind (with the exception, so far as known, of one man only, the Greek, Aristarchus), and continued to be generally accepted for a long time after the death of Copernicus. That the heliocentric conception is the right one, is now as fully established as any other astronomical fact whatsoever. Yet it seems so unplausible that thousands of generations of star-gazers failed to consider it even as a possibility, and when it was suggested by Aristarchus of Samos, a Greek living in the third century B.C., it gained no adherents, and was totally ignored thereafter for more than 1700 years.

Heliometer. A micrometer device with divided object glass, the parts of which are movable with a micrometric screw, so as to bring images of nearly adjacent celestial objects together. It is

used for measuring small angular separations, and is the device that enabled Bessel to determine the parallax of the star 61 cygni, thus for the first time accurately determining a stellar distance.

Hour angle of a celestial object. The angle of the plane between the meridian of the observer and the plane of a great circle passing through the poles and the opposition of the object under consideration. The angle is usually expressed in hours, as indicating the distance in time of the object from the meridian of the observer. One hour of time represents 15 degrees, necessarily, since 24 times 15 are 360, the number of degrees in an entire circle.

Interferometer. An instrument devised by Professor A. A. Michelson, the purpose of which is to bring together two beams of light to note when their superposed spectra give fringed images of lines. By adjusting the mirrors that reflect the light the fringes may be dissipated, showing that the waves of the two beams are coincident. An especial type of interferometer, consisting of a beam about 20 feet long with the reflecting mirrors adjusted near its end, has been used, in connection with one of the great telescopes at Mt. Wilson Observatory, to measure the actual diameters of a few of the largest stars—the first one so measured being Betelgeuse, the big shoulder-star in the constellation Orion. The actual measurements of the stars with the interferometer at Mt. Wilson were made by Dr. Pease.

Latitude. The angular distance on the earth surface north or south of the equator. A degree of latitude is about 69 miles, and the variation in length between equator and pole is not very great, but nevertheless significant in an astronomical sense. Owing to the flattening at the poles, the degree lengthens slightly as the polar region is approached. The precise determination of a degree

of latitude was a problem not solved until well toward the close of the 17th century. Up to that time, it was debatable whether the earth is an oblate or a prolate spheroid. A French expedition to measure a degree of arc at the equator, checked by another expedition measuring a degree of arc in northern Europe virtually settled the question. It was the new and correct determination of a degree of arc, giving a new measurement for the size of the earth itself, that enabled Newton to confirm his idea of gravitation as the force holding the moon in its orbit. Galactic latitude is the angular distance on the celestial sphere from the medium plane of the Milky Way. Heliographic latitude similarly measures the sun's sphere north or south of the sun's equator. The simplest method of measuring or determining the latitude of any place on the earth's surface is to observe the shadow of an upright peg (gnomon) on a level surface, and thereby to find the angular distance of the sun from the zenith. This angle added (algebraically) to the sun's latitude at the time of observation is the latitude of the place. On the day of either equinox, when the sun is at the equator, the angular distance obviously gives the latitude directly.

Libration of the moon in longitude. An apparent oscillation caused by the unequal velocity of revolution of the moon in its orbit, combined with its uniform velocity of rotation on its axis, and also caused by the daily rotation of the earth, bringing the observer into different positions of view at moon rising and setting. Thus we see more than half of the moon in its longitudes (Abbot).

Light-year. The distance traveled by light in a year, amounting to about 6,000,000,000,000 miles. The light year is thus a distance and not a period of time, yet it is equally obvious that time

and distance are here interdependent. If we were stationed one light-year from the earth, we should witness events one year after their time of actual happening, and so for any number of years. Since light radiates in all directions, we may think of space as being filled with successive concentric spheres each of which is the position of the waves of light representing a moment more or less remote according to the distance. A curious feature of this imagining is that, if we stop to reflect, we shall see that the earth no longer remains in the spot where it was when the event occurred. Yet since light travels in straight lines, we should seem to see the earth in its old location. If we were even a single light-year away, we should be looking at an earth and locating it in a position from which it has now departed by about 327,000,000 miles. Of course, the same thing holds under the actual conditions of our observation of the stars. These bodies are in motion, and no one of them really exists where we seem to see it. Even stars at a moderate distance are billions of miles removed from the point where we now see their images. The modern astronomer is likely to speak of star distances in terms of "parsecs," a parsec being 3.26 light-years.

Limb of the sun, planets, and satellites. The edge of the visible disk. The astronomer says "right or left limb" where a layman would be likely to say "right or left side."

Longitude. Angular distance on the earth's surface east or west of the meridian of Greenwich, England. It may be reckoned in degrees or in hours, one hour equalling 15 degrees. In either case, minutes and seconds are the smaller divisions. Since the sun or any other stellar body, owing to the earth's rotation, crosses 15 degrees of longitude in an hour, it is obvious that one degree is crossed in four minutes. The longitude of a place may be deter-

mined by noting the minute when the sun is on the meridian, and applying the equation of time, for the day. Standard time for a zone is reckoned from meridians at even-hour distance from Greenwich—the critical meridians in the United States being 75 degrees west for eastern standard time, and 90 degrees, 105 degrees, 120 degrees, respectively for Central, Mountain and Pacific time. If you live east of critical meridian, the sun will come to your meridian earlier than the clock-hour, by four minutes for each degree of distance, and of course the conditions are reversed if you live west of the critical meridian. It is a simple and interesting experiment to test your location by observing the sun's shadow, bearing these conditions in mind. *Celestial longitude* is measured all in one direction round the sphere, reckoned from the point of the vernal equinox in the constellation Pisces (still called the *sign* of Aries).

Lunation or the lunar month, is the time required for the moon to complete all its phases; otherwise the synodic. As the sun constantly tugs at the moon, modifying the effect of the earth's gravitation pull, the motions of that body are greatly modified from the simple ellipse that would be its orbit if there were no such disturbing influence, coupled with minor disturbances due to Jupiter and the other planets. The calculation of the moon's orbit becomes exceedingly complicated and the full theory of the lunar movements has been worked out only by successive generations of calculators.

Magnitude of stars. Ptolemy in the Almagest, summarizing the knowledge of antiquity, lists the stars in six groups as to magnitude, from brightest to faintest. First magnitude stars are few in number, and the number increases with each successive magnitude. The total number of stars of the sixth magnitude, or stars

visible to the naked eye, is about 6000. But even the crude telescope of Galileo brought vast numbers of stars to view, and the modern telescope, with the aid of the photographic plate, shows increasing galaxies to the 22nd or 23rd magnitude—the total number thus revealed being variously estimated at from 30,000,000,000 to 100,000,000,000. Modern studies, particularly by Pickering, of Harvard, developed a photometric scale, by which stars are classified as to fractional magnitude. A visual photometer makes possible the measurement of a difference of about one-tenth of a magnitude, but the photoelectric photometer detects one-hundredth of a magnitude difference. Following a suggestion of Pogson, a first magnitude star is regarded as precisely one hundred times brighter than a sixth magnitude star. The scale is by geometric progression. A star that is one magnitude brighter than another is 2.512 times brighter; while if two magnitudes brighter it is the square of that number (2.512^2). This value 2.512 is called the magnitude ratio, or light ratio. As stars originally classed as of first magnitude differ among themselves in brightness, a plan was adopted of extending the scale negatively. Thus the first magnitude stars Altair (0.9) and Aldebaran (1.1) are close to unity, but Vega and Sirius are much brighter. So Vega, which is 0.8 magnitude brighter than Altair, has a magnitude of 0.1, and Sirius, which is 2.5 magnitudes brighter than Altair, is of magnitude minus 1.6. The scale continues negatively for the planets, and culminates with the sun, which has a magnitude of about minus 26.7.

The stars of the accompanying table are arranged in the order of their right ascension, or longitude, so that their sequential position from west to east is indicated. The table shows declinations (latitude) also, so that the general position of the star may

be readily located. In the sky, the two stars making the rim of the Big Dipper are about ten degrees apart—so this serves as a yard-stick to give one a general idea of star distances. The pole star is at an angular distance above the northern horizon equal to the latitude of the place of observation—which serves as a larger yard-stick. The zenith, of course, is 90 degrees from the horizon. Mars or Jupiter if visible will serve to locate the ecliptic.

The list of first magnitude stars follows:

THE FIRST MAGNITUDE STARS

(Arranged in order of Right Ascension. Declinations are also given, so that the stars may readily be located.)

No.	Star	Constellation	Right Ascension 1900 H	M	Declination 1900		Magnitude	Spectrum
1	Achernar.....	Eridanus.....	1	34.0	−57°	45′	0.6	B5
2	Aldebaran....	Taurus.......	4	30.2	+16	18	1.1	K5
3	Capella......	Auriga.......	5	9.3	+45	54	0.2	Go
4	Rigel........	Orion........	5	9.7	− 8	19	0.3	B8
5	Betelgeuse....	Orion........	5	49.8	+ 7	23	0.6−1.2	Mo
6	Canopus.....	Carina.......	6	21.7	−52	38	−0.9	Fo
7	Sirius........	Canis Major..	6	40.7	−16	35	−1.6	Ao
8	Procyon......	Canis Minor..	7	34.1	+ 5	29	0.5	F5
9	Pollux.......	Gemini.......	7	39.2	+28	16	1.2	Ko
10	Regulus......	Leo..........	10	3.0	+12	27	1.3	B8
11	Alpha Crucis..	Crux.........	12	21.0	−62	33	1.0	B1
12	Beta Crucis...	Crux.........	12	41.9	−59	9	1.5	B1
13	Spica........	Virgo........	13	19.9	−10	38	1.2	B2
14	Beta Centauri	Centaurus....	13	56.8	−59	53	0.9	B1
15	Arcturus.....	Boötes.......	14	11.1	+19	42	0.2	Ko
16	Alpha Centauri	Centaurus....	14	32.8	−60	25	0.3	Go
17	Antares......	Scorpius......	16	23.3	−26	13	1.2	Mo
18	Vega.........	Lyra.........	18	33.6	+38	41	0.1	Ao
19	Altair........	Aquila.......	19	45.9	+ 8	36	0.9	A5
20	Deneb.......	Cygnus......	20	38.0	+44	55	1.3	A2
21	Fomalhaut....	Piscis Austrinus.....	22	52.1	−30	9	1.3	A3

Adapted from
"Fundamentals of Astronomy," Mitchell-Abbot.

Mass-luminosity law. The relation between the mass of a star and the amount of energy radiated by it has been estimated by Eddington, covering a range of absolute magnitude between minus 4 and plus 13, and a range of mass from about one-sixth to 25 times the sun's mass. He establishes a curve based on theoretical considerations, which agrees well with the absolute magnitudes and masses of known stars. Therefore there appears to be a definite physical relationship between the mass of a star and its luminosity, which will make possible the calculation of one if the other is known. The absolute magnitudes 1, 5, 0, and minus 4 correspond to the masses 0.3, 0.7, 3.4, 25 times the sun's mass, respectively.

Meridian. An imaginary plane including the earth's poles and extending to the celestial sphere. The theoretical number of meridians is almost infinite, but the meridians of practical importance for navigation are numbered in degrees from 1 to 180 east and west of Greenwich, England, the position of zero meridian. The sun, circling the globe in 24 hours, necessarily compasses 15 degrees in an hour. So for the computation of standard time, the 15th, 30th, 45th, 60th, and sequential meridians at intervals of 15 degrees are the critical meridians for the adjustment of the standard clock. Longitudes may therefore be named either in degrees or in hours. Thus 5 hours west longitude is represented by 75 degrees. The "local meridian" is at the zenith of the point of observation.

Meteorite. An object that falls from the skies, out of the depths of space. Meteorites are composed of terrestial elements, many of them being largely alloys of iron and zinc, others being of the character of rocks, allied to granite and basalt. Meteorites have peculiar interest because they are the only objects that come

to us from an extra-terrestrial source. They are believed to be fragments of "world-stuff" that may in some cases represent dismembered comets. Astronomers are not fully agreed as to whether meteorites are of one substance with the so-called meteors, or shooting-stars, which flash through the upper atmosphere and are there vaporized.

Nodes of an orbit. The points at which the plane of an orbit, intersect with the plane of the earth's orbit; or, in case of the moon, the point at which the orbit of the plane intersects with the plane of the earth's equator.

Opposition of a superior planet. The position at which the planet is in line of the earth and sun. This is obviously the position at which the planet is nearest the earth, giving best opportunity for observation. Mars in opposition has long been used for parallax studies, to determine indirectly the sun's distance. The little asteroid or planetoid, Eros, comes nearer the earth even than Mars, when at opposition, owing to the extreme ellipticity of its orbit. Therefore Eros offers exceptional opportunity for parallax studies. Special expeditions were formed to test the parallax of Eros in 1901.

Parallax. The angle subtended at a star by the radius of the earth's orbit is called the parallax of the star. The largest parallaxes known are 0.76 seconds, shared by two stars, the double star Alpha Centauri and an eleventh magnitude star about 2.2 degrees from it, which may or may not be physically connected with it. Parallaxes determined by direct telescopic observation are called trigonometric parallaxes. Spectroscopic parallaxes depend on the study of the relative intensities of certain pairs of lines in the star-spectra. The method was developed at the Mt. Wilson Observatory by Adams and Kohlschütter.

Perihelion. The point of a planetary orbit that is nearest the main focus of the ellipse. Our earth is in perihelion about the 21st of June, being then farthest from the sun. The opposite of perihelion is aphelion.

Planets. Members of the sun's family. The planets known to the ancients were Mercury, Venus, Mars, Jupiter and Saturn. The earth of course was not then recognized as a planet. Toward the close of the 18th century the planet Uranus was discovered by Herschel, and toward the middle of the 19th century the planet Neptune. Trans-Neptunian planets were suspected to exist. One was discovered in January, 1930, at Lowell Observatory. The minor planets, called asteroids or planetoids, occupying a position between Mars and Jupiter were unknown until the first day of the 19th century, when the first one was discovered by the Italian astronomer, Piazzi. Many hundreds of these little planets are now known. The following table gives the sizes, distances from the sun, and the periods of revolution of eight major planets only; data not being as yet available for the ninth.

Planets	Distances from sun. Earth's 1.	Number of Satellites	Mean dis. from sun in miles	Periods of Revolution round sun in years	Diameters in miles
Mercury.......	0.4	0	36,000,000	0.25	3,000
Venus..........	0.7	0	67,000,000	0.63	7,700
Earth..........	1.0	1	93,000,000	1.0	7,920
Mars..........	1.5	2	141,000,000	1.8	4,200
Asteroids.......	3.0±	..	280,000,000	3 to 9	10 to 490
Jupiter.........	5.2	9	483,000,000	11.9	87,000
Saturn.........	9.5	9	886,000,000	29.5	72,000
Uranus.........	19.2	4	1,780,000,000	84.0	32,000
Neptune.......	30.1	..	2,790,000,000	165.0	35,000

Prominences of the sun. Spectacular protrusions that extend out from the border of the sun, and are particularly visible at an eclipse. Sir Norman Lockyer, the English astronomer, devised a method of studying the prominences spectroscopically under ordinary conditions, and in the light from the prominence discovered lines of a new element, which he named Helium. The same lines were independently observed at about the same time by the Frenchman Janssen through study of the chromosphere at an eclipse in India.

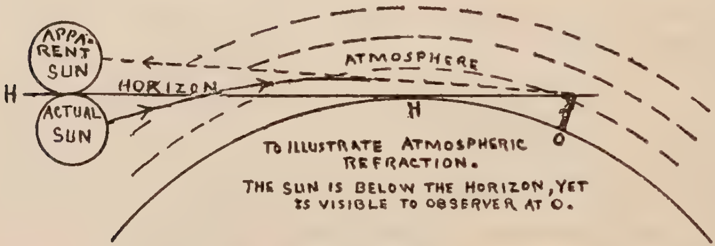


FIG. 103.

Reduction of a star's position. When the position of a star has been accurately observed, modification of the apparent position must be made in order to find the true position. Allowance must be made for atmospheric refraction, particularly if the star is not very near the zenith (taking account of temperature and humidity), for the earth's motion, both orbital and rotational, for aboration of light, and for nutation. For purposes of comparison with earlier star-charts, proper motion due to the transitional flight of the solar system must also be considered. The formulæ for "reduction" were developed largely by the German astronomer Bessel, who first unequivocally determined the parallax of a star.

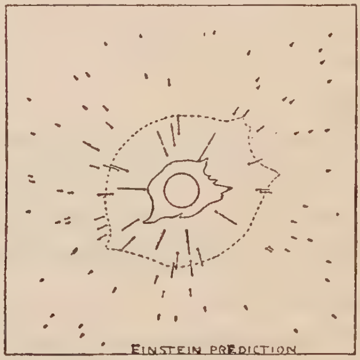
Refraction. The bending of the rays of light on passing from one medium to another is strikingly illustrated by thrusting a stick

slantwise into the water. A similar bending occurs when light comes from outer space into the earth's atmosphere. The astronomical observer must take this into account, particularly when the object observed is near the horizon. Refraction is there so marked that the displacement amounts to upward of half a degree, so that when the sun seems to rest with its lower limb just at the horizon, the entire body of the sun is really below the horizon. At an elevation of 45 degrees, however, the refraction ordinarily amounts to only about one minute of arc, and when the star is very close to the zenith, refraction almost disappears.

Refracting telescope. A telescope that uses glass lenses instead of a reflecting mirror. This until the time of Herschel was the only telescope prominently used. The great refractors, such as that at Lick Observatory, with 36-inch lens, seem to approach the limit of magnitude for telescopes for this class, at least under existing conditions of optical science. Reflecting telescopes are made much larger, that of Lord Rosse, at the middle of the 19th century, having a six-foot speculum. The greatest reflector at Mt. Wilson has a 100-inch mirror. The construction of a reflector with 200-inch mirror was contemplated in 1930.

Relativity. The famous relativity hypothesis of Professor Albert Einstein attained extraordinary prominence and gained an enthusiastic following on the part of many of the most prominent mathematical astronomers of the early 20th century. No one has been able to state the full implications of the theory at once briefly and clearly. It was founded, however, upon tangible experiments, and the only methods suggested for its testing are astronomical methods. The ether-drift experiments of Michelson and Morley, made in 1887, did not reveal as large a displace-

ment of the ether as had been expected, though they were not negative, as is commonly reported. Professor Einstein, however, regarded them as negative, and, declaring that such a test could never be successful, developed his relativity hypothesis, according to which the length of measuring instruments is shortened in the direction of movement in direct proportion to the rapidity of the movement—so that light will appear to take the same time in traveling longitudinally and transversely. The astronomical



From *Time and Relativity*, by Prof. Charles Lane Poor; pp. 20-21.

A. THE ECLIPSE OBSERVATIONS.
This figure shows the relative displacements of 92 stars as observed by Campbell at the total solar eclipse of September 21, 1922, and is from a direct tracing of the star chart in Lick Observatory Bulletin, No. 346. In that chart, however, the displacements of 21 stars were omitted: these have been added to make the above diagram complete.

B. THE EINSTEIN PREDICTION.
This figure shows the theoretical Einstein displacements of the 92 stars observed by Campbell. By comparing these Einstein displacements with those observed by Campbell one may form a clear idea as to the truth of relativist's repeated assertions: "These results (Campbell's) are in exact accord with the requirements of the Einstein theory."

FIG. 104.—Solar Eclipse Observations of September 21, 1922. (From charts by Prof. Charles Lane Poor, said to be based on Lick Observatory Bulletin No. 346.) Ninety-two stars are compared as to their observed displacement in contrast with the displacement predicted by the Einstein formula.

tests of the theory, proposed by Professor Einstein himself, are (1) explanation of the modified perihelion-shift of the planet Mercury; (2) observation of the apparent shift of position of stars whose light comes near the sun, as noted in an eclipse;

and (3) shift of the spectrum lines toward the red when light issues from a body of great mass. Professor Charles Lane Poor appears to demonstrate that the Mercury-perihelion test is altogether inconclusive, and that the star-shift test fails utterly to demonstrate any such modification of the light waves as the Einsteinian prediction calls for. Professor Dayton C. Miller, working at Mt. Wilson at an elevation of 6000 feet, appears to demonstrate the ether drift, notwithstanding the declaration of the author of relativity theory that such a demonstration cannot be made. The theory seems therefore to lack the support in tangible experiment it was supposed to have. The third test, however, is believed by many spectroscopists to have been met successfully, particularly in study of the spectrum of the white dwarf star known as the companion of Sirius. Whatever the ultimate estimate of the theory of relativity, it has had tremendous influence on the mathematical astronomers of our time.

Right Ascension. The term used for the equivalent of longitude showing the meridional position of a celestial body. Right ascension is calculated eastward throughout the entire 360 degrees, from the meridian of the vernal equinox, or that which passes through the point of intersection of the planes of the earth's equator and the ecliptic. Right ascension, like longitude, may be stated in terms of degrees or of hours—one hour representing 15 degrees. It is somewhat confusing that minutes and seconds are also used in either case; for of course, since one hour represents 15 degrees, a minute of time is very different from a minute of arc. The sun or a star crosses one degree of arc in four minutes of time. One-fourth of a degree of arc, or 15 minutes of arc, therefore, equal one minute of time.

Satellite. The attendant of a planet, of which our moon is the

type. In comparison with the earth, the moon is much larger than is any other satellite in comparison with its planet. But several of the satellites of the system are larger than the moon. Had the satellite of Mars been comparable to the moon in size, so that they could be observed with the naked eye from the earth, it is more than possible that the ancients would have conceived the idea of the heliocentric system. But since all the satellites are telescopic, the object lesson was not given until Galileo turned his telescope on the planet Jupiter.

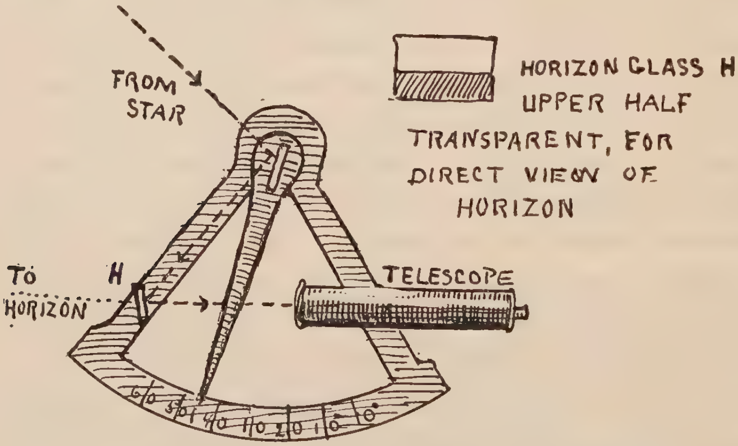


FIG. 105.—The Operation of the Sextant. (Adapted from Smart's *The Sun, the Stars, and the Universe.*) The image of the sun or a star is brought to the horizon, and the pointer indicates the elevation. At zero of the scale, the two mirrors are parallel.

Sextant. The instrument used by navigators to determine the altitude of the sun or another celestial body. The instrument is aimed at the horizon, and is so constructed that a reflected image of the sun or star may be brought to the horizon, a graduated scale, read with a microscope, revealing the exact angle of altitude. The angle really used in the subsequent calculation is not

the angle of altitude, but the complementary angle of the zenith-distance—sometimes spoken of as the "zenith angle." The navigator measures the altitude directly, because he can focus on the horizon, but has no correspondingly accurate measure method of determining the vertical. The astronomer, in determining the position of a star, measures the zenith-distance angle directly, since he can determine the vertical with plumb-line and double-level. The Greek astronomer, Eratosthenes of Alexandria, recog-

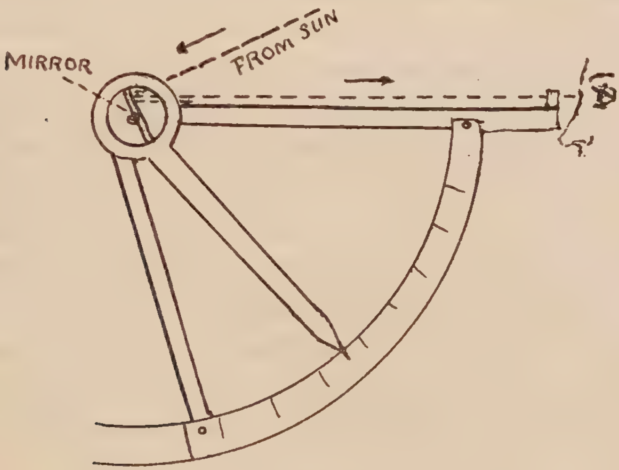


Fig. 106.—A Modified Cross Staff.

nised that the zenith-distance angle is equivalent to the angular distance along the earth's surface between the point of observation and the point at which the star or sun is directly at the zenith. This principle is used by the navigator in determining his location, since the positions of numerous stars are given in the Nautical Almanac, which he always consults in completing his calculations. The sextant, which measures the position of the celestial body, was developed in modern times, but is the

outgrowth of the old quadrant and cross-staff and astrolabe used in antiquity and in particular by the mediaeval Arabs.

Spectroscope. An instrument for splitting up the rays of light and spreading them out into a spectrum the so-called Fraunhofer lines of which reveal the chemical composition of incandescent gases from which the light comes or gases through which it shines. The original spectroscopes were prisms of glass. Another type of spectroscope, utilizing finely ruled lines on a metal surface, was perfected by Professor Rowlands of Johns Hopkins University. The spectroscope reveals not only the chemical composition of stars, but movement of stars in the line of sight. If the star is approaching, the Fraunhofer lines are shifted towards the violet end of the spectrum. If the star recedes, the shift is toward the red end. The observer calculates from the amount of shift the rate of movement of the star. Binary systems of stars are also revealed by the doubling of a spectrum line as the stars shift position. Modifications of lines are also interpreted in terms of stellar parallax. The spectroscope, particularly in conjunction with the photographic plate, has become an observatory adjunct only second in importance to the telescope itself.

Stars, numbers and distance of. Investigations of Seares and Van Rhijn at the Mt. Wilson Observatory led to the estimate of the total number of stars of the 21st magnitude as approximately one billion. No satisfactory way of determining the limiting magnitude of the faint stars nor their total number was developed, but theoretical investigation indicated that the total number of stars revealed by the largest telescope (the 100-inch mirror at Mt. Wilson) at present in use is of the order of 30 billion. Other estimates have made the number much larger, but

the matter is hardly significant. The difference between 30 billion stars and 100 billion is only a matter of words. The total light of all the stars in the sky is estimated by the Mt. Wilson ob-

NUMBER OF STARS BRIGHTER THAN GIVEN VISUAL MAGNITUDES

(According to Drs. Seares and Van Rhijn)

Visual Magnitude	Total No. of Stars	Ratio
4	530	
		3.1
5	1,620	
		3.0
6	4,850	
		3.0
7	14,300	
		2.9
8	41,000	
		2.8
9	117,000	
		2.8
10	324,000	
		2.7
11	870,000	
		2.6
12	2,270,000	
		2.5
13	5,700,000	
		2.4
14	13,800,000	
		2.3
15	32,000,000	
		2.2
16	71,000,000	
		2.1
17	150,000,000	
		2.0
18	296,000,000	
		1.9
19	560,000,000	
		1.7
20	1,000,000,000	

servers as the equivalent to 1076 stars of magnitude 1.0. The uncertainty in the total number does not affect this value greatly, as the stars magnitude greater than 21 furnish 98 percent of the total light. As to distance, stars range from 4.3 light-years to thousands of times that. Only 8 or 10 stars are within 16 light-years of the earth. Fath names a few of the nearest, including Alpha Centauri (4.3), Barnard's proper-motion star (6.0), Van Maanen's proper-motion star (8.0) Sirius (8.6), Procyon (10), 61 Cygni (11), and Altair (16). There is evidence, Fath adds, that some of the most distant stars may be as much as 1,000,000 light-years away. It would hardly be claimed, however, that the evidence for such distances is comparable in authenticity with the measurements of the comparatively short distances.

Stars, sizes. Where stars differ enormously in both apparent and actual brightness, there is no corresponding difference in mass, according to the calculations of Professor Eddington. He estimates that, in general terms, a star will not become luminous if it is less than about one tenth the size of the sun, and will not hold together if it is more than about 100 times larger than the sun. There is a balance between gravitational force and the force of radiation, the latter tending to dissipate the substance of the gaseous star. Stars are of extreme brightness when they are in a gaseous condition, and therefore exceedingly bulky. A dwarf star, like the white companion of Sirius, may have an exceedingly bright surface, but its total luminosity is slight, because of its small bulk. The fact that all stars are of comparable size is one of the most striking developments of Eddington's mathematical appraisal of star conditions.

Telescopes. Telescopes are of two types, refracting and reflecting. Refractors consist essentially of glass lenses so ground

and adjusted as to minimize the spherical and chromatic aberration. Reflecting telescopes have a parabolic mirror or speculum at the bottom of the tube, so that in using them the observer does not look toward the stars but at a reflected image. The famous instruments at Yerkes Observatory and at Lick Observatory are refractors. The most famous instruments at the Mt. Wilson Observatory are the great 60-inch and 100-inch reflectors. Each type has its own field of usefulness.

Transit instrument. The meridian telescope and meridian circle telescope are instruments pivoted on very firm pillars in such a way that they can be rotated in the north and south line, but not laterally. By exceedingly delicate adjustment of the axles, the instruments are made to point directly to the meridian, or as nearly so as is mechanically possible. A spider-web line at the center of the field enables the observer to note the exact instant when a star reaches the meridian. He records the moment by pressing a button which registers a mark on the chronograph. The meridian instrument is one of the most important parts of the equipment of most observatories. It performs a function, in locating the precise position of a star, that no other instrument can duplicate. An instrument that is to be used for following the movements of stars and photographing them must be mounted in a quite different way. An instrument that can thus swing about is said to be equatorially mounted. In the modern observatory, the movement of the telescope is determined by clock work, so that the instrument follows the movement of a star, and the image of the star is registered as a point on the photographic plate, even though exposure may have been for a term of many minutes, or even an hour, during which the star has apparently shifted position by many degrees.

Weight. The relative mass of an object as compared with the mass of the earth is called weight. Mass and weight are nearly synonymous terms, but not quite, inasmuch as the weight of an object would differ vastly if the weighing were done on other planets, or on the moon, whereas the mass would not change, being something fixed and invariable. For practical purposes, here at the earth's surface, the words mass and weight are interchangeable. Yet even here it may be recalled that the weight of a given mass of any substance may vary appreciably if the weighing is done at different latitudes. Since the earth bulges at the equator, the distance of its surface there from the center of the globe is greater than the distance of the surface toward the polar region. Therefore a "pound" of anything would weigh less at the equator than it would, say, in Alaska. The discrepancy was first discovered by an astronomer who took to the equatorial region a clock the pendulum of which beat seconds in France, but was found to swing more slowly in the tropics. The rate of swing of the pendulum may be used to measure altitudes, on the same principle. The matter making up the crust of the earth weighs less than the matter toward the center of the globe, the total mass of the earth being more than twice what it would be if it were composed exclusively of such rocky substance as makes up the crust.

Year. The year is the period required by the earth to make a complete circuit of its orbit. Unfortunately this is not an exact number of times its period of rotation. Hence the difficulty that calendar-makers have experienced in all ages. The anomalistic year is equal to the interval between two successive passages of the earth through perihelion. It is about five minutes longer than the sidereal year, which is the interval between the sun's succes-

sive passages of the same star. The mean solar year, or the interval between two successive vernal equinoxes, is shorter by about twenty minutes than the sidereal year, owing to the precession of the equinoxes. The mean solar year is the year of everyday life. The astronomer's year is the sidereal.

Zenith. The point directly overhead, as practically determined by the imaginary extension of the plumb-line. Otherwise stated, a radius of the earth extended from the point of observation. Naturally the zenith changes for any individual observer with every change of his position. The location of the zenith is exceedingly important in astronomical observations, since the position of a star, in declination, is determined by measurement of its angular departure from the zenith. The importance of this angle for purposes of measurement of arcs of the earth's surface was understood by Eratosthenes, the Alexandrian Greek who first measured the size of the earth. The amateur may study the angular distance of the sun from the zenith—conveniently spoken of as the "zenith angle"—by adjusting a peg or nail vertically on a level surface, so that the shadow is clearly defined. The angle then actually measured is not the zenith angle itself but its opposite. But of course opposite angles are equal, so the two things are equivalent. The angle observed, according to the Eratosthenes principle, shows the angular distance along the earth's surface of the so-called sub-solar spot, or point directly below the sun at the moment of observation. For example, if the angle is 60 degrees, this shows that the sub-solar spot is 60 degrees distant. And since a degree is approximately 69 miles, this is equivalent to saying that the place where the sun is on the zenith is (60 times 69) 4140 miles distant. This is essentially the principle utilized by the navigator in determining his position

as to latitude and, with the aid of a chronometer, as to longitude. Much of the work of government observatories is directed to the calculation of the exact positions of sun, moon, and a large number of conspicuous stars year by year, to furnish the tables of the Nautical Almanac without which safe navigation would be impossible.

Zenith-angle. The angular distance of the sun from the zenith, referred to under the preceding heading. In the text we saw Eratosthenes measuring this angle, and thereby measuring the earth itself. Anyone may imitate his example, and a good deal of amusement may be gained by the process. Of course no one nowadays need care to measure the earth, but it may be amusing to measure one's own location on the earth—determining for oneself the latitude and longitude of the place of observation. It is also of interest to reverse the process, and determine time by observation of the sun's zenith angle. In fact, an entire series of amusing experiments, or even games, may be developed through utilization of the Eratosthenes principle. This principle, it will be recalled is that the sun's angular distance from the zenith (called here the zenith-angle) represents also the angular distance along the earth's surface between the observer and the sub-solar spot. This simple principle is the only one that must be borne in mind. Its application gives opportunity for the experiments just referred to. The zenith angle may be measured with an upright peg or nail ("gnomon"), as Eratosthenes measured it, and as is suggested in the preceding reference. But there are several other methods equally simple. Some of these are here illustrated. One of the most interesting is to use your watch as an astrolabe, a purpose for which it is admirably adapted, since its circumference is divided into degrees, and the hands serve

as pointers. If you hold the watch with its edge toward the sun, just oblique enough so that the sun strikes across the dial, the watch being suspended, the upright diameter (hour XII to hour VI) gives the vertical, and a shadow cast across the center of the dial by a pencil held horizontally enables you to read the zenith angle directly. Or one of the hands of the watch may be manipulated to point directly at the sun (so that the shadow

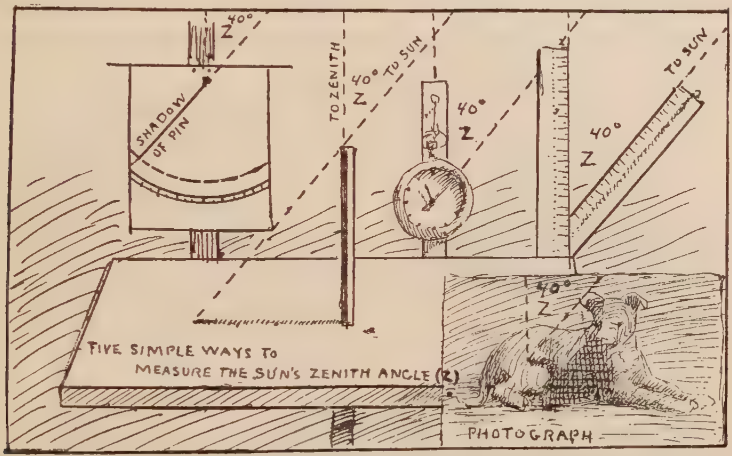


FIG. 107.—The Sun's Zenith Angle. Five simple ways to determine the sun's altitude at a given moment, and thereby to estimate, either directly (watch, Protractor-like dial) or by subsequent measurement, the Zenith Angle—which is here an angle of 40 degrees in each case.

disappears behind the hand), thus indicating the angle, and enabling you to read it as readily as you tell time by the watch. Suppose, for example, the hour is precisely ten, and, holding up the watch, you find that the hour hand points directly to the sun. This indicates that the sun's zenith distance is 60 degrees—and that therefore the sub-solar spot is 60 degrees away at the surface of the earth. You virtually survey this distance by glancing at your watch. You know that an airplane, flying 69 miles (the

length of a degree) per hour would require 60 hours to fly to the spot directly beneath the sun's present position. This knowledge enables you to devise various puzzles, or experiments, as already suggested. Two or three of these are here illustrated. It may amuse you to develop others for yourself. The illustrations will show that photographs may be used for the same purpose, provided a shadow is shown distinctly, and that the picture was taken with the line-of-sight of the camera at right angles to the direction of the sun's rays. But full explanations are given in the captions to the pictures themselves.

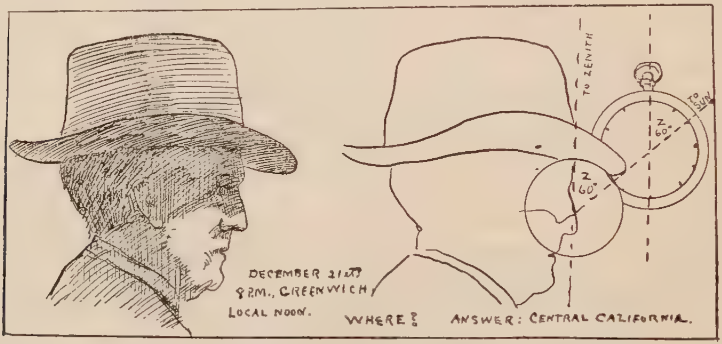


FIG. 108.—Sun's Zenith-Angle Test Illustrated. Explanation: Zenith angle 60 degrees. Sun on Tropic of Capricorn, 23.5 degrees beyond Equator. Location of picture therefore (60 minus 23.5) about 36.5 North latitude. At "8 P.M. Greenwich" the sun is on Meridian 120 (8 times 15) West. Parallel 36.5 North and Meridian 120 West intersect in central California.

Zodiac. The zodiac is about sixteen degrees wide, eight degrees on each side of the ecliptic. The name is from the Greek, derived from the fact that the constellations in this belt, with one exception (Libra) are figures of animals. The conception of the zodiac itself is derived simply from the fact that the moon and planets known to the ancients never go farther than 8 degrees from the ecliptic, which is the plane of the earth's revolu-

tion about the sun. The so-called signs of the zodiac were originally of unequal length, but Hipparchus unified them, making each 30 degrees in length. The signs are still used and the constellations bear their original Greek names, or Latinized forms of them, though the precession of the equinoxes has shifted the relations of signs and constellation. The spring constellations are

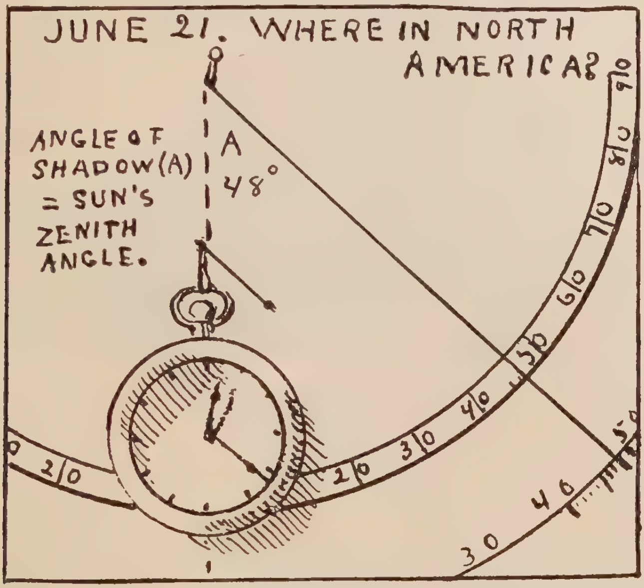


FIG. 109.—A Sun's Zenith-Angle Puzzle. Answer: Point Barrow, Alaska. (Explanation: The midday zenith angle, about 48 degrees, indicates a location about 48 degrees north of the Tropic of Cancer (where the sun is)—that is to say, about 71 degrees North latitude. The region of Point Barrow (71.4 North) is the only such location on the continent.

Aries, Taurus, and Gemini; the summer constellations, Cancer, Leo, and Virgo; the autumn constellations Libra, Scorpius, and Sagittarius; the winter constellations Capricornus, Aquarius, and Pisces. The animal figures which ornamented many of the 18th century star-charts, and even more modern ones, were drawn by

notable artists of the periods. It is more than likely that the original star-chart of Ptolemy had equally attractive ones by Greek artists, but the ancient manuscripts have not been preserved, and the copyist of later generations did not of course make facsimile reproductions. The modern astronomer defines the position of stars according to Declination and Right Ascension (the equivalents of latitude and longitude), instead of saying, as an ancient astronomer would say, "the star in the heart of the lion," or the "star at the tip of the lesser bear's tail." Yet the names of the constellations are retained, notwithstanding the obvious inconvenience of having constellational areas of such irregular bounds. After all, this is not very different from the retention of irregular boundaries for States and Countries, where there is no natural landmark. In each case there are practical reasons why it would be difficult to break with tradition.

C

CHARTS OF THE CONSTELLATIONS

The most famous of ancient star-charts was that of Hipparchus, which was preserved and extended by Ptolemy, and by him transmitted to the Arabs, who subsequently brought it to Spain, where it stimulated the astronomers of Alfonso X. to make star-charts that appeared under title of the Alfonsine Tables. The greatest chart-makers after the revival of interest of astronomy in central Europe in the 16th century were Tycho

Brahe and John Bayer. The latter was a Bavarian, who is especially to be remembered, not only for the accuracy of his

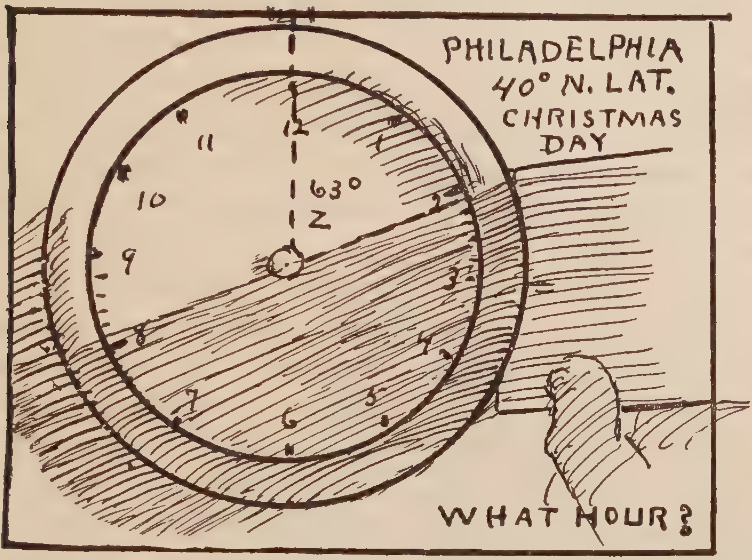


FIG. 110.—The Time by a Handless Watch. Answer: Twelve o'clock, Noon, Eastern Standard Time. Explanation: Zenith angle, about 63 degrees. Sun near Tropic of Capricorn, about 23 degrees beyond the Equator. Philadelphia is at 40 degrees North latitude. So on this day the zenith angle could not be smaller than 63 degrees, and must be larger except when close to local meridian. Philadelphia is on the 75th meridian (five hours west of Greenwich), and on Christmas day the sun is exactly on time; so—within the limits of accuracy of the measurement—the hour is shown as precisely 12 M. Eastern Standard Time, or 5 P.M. Greenwich.

(If the watch hangs perfectly vertical, and the shadow is carefully gauged, this handless watch may show the time at least as accurately as the average watch used in the ordinary way. Accuracy depends on holding the shadow-casting card or pencil exactly level (horizontal), and noting that the edge of the shadow is precisely as far from VI below as from XII above, and thus passes through the center of the dial. Any hour when the sun shines may be similarly gauged, with the aid of a map or globe. Thus to tell the time with a handless watch is in itself a rather amusing stunt. It works anywhere, if you know your location.)

observations, but for the introduction of a new system of star-naming, which all astronomers were to use in future.

Bayer was a preacher, whose eloquence made him known as the "mouth piece of Protestantism." His famous *Uranometria,* published in 1603 was by far the most comprehensive star-chart to appear in pre-telescopic day. It gave the approximate positions and magnitudes of some 500 stars in addition to the 777 which formed the renowned catalogue published by Tycho Brahe only one year earlier.

Bayer's chart, it will be understood, was a record of stars as they are seen in the sky, with no implications as to the nature of the firmament in which the stars appear. His chart, however, did have this particularity: it presented the conventional traditional figures of the constellations—Big Bear, Little Bear, and all the rest—as they would appear when viewed from the earth, and not in the reverse position hitherto given them—as if viewed from the fictitious outer surface of the imaginary celestial sphere.

The American astronomer, B. A. Gould, himself the author of a celebrated South American star-chart (Uranometria Argentina) commenting on this, notes that this change, obviously a betterment, by no means commended itself to the astronomers who came after Bayer, but on the contrary was vehemently criticised, because it implied a reversion of some of the figures, thus interchanging right and left.

No doubt this was an inconvenience, accounting for the protests of Hevelius and of Flamsteed, both of whom made notable additions to the work of star-charting, after telescopes had brought new cohorts to view.

Flamsteed even attributed the inversion to a supposed misinterpretation of Ptolemy's phraseology. Other critics thought

Bayer had merely erred through overlooking the inversion produced by printing from an engraved plate in reproductions of Ptolemy's early catalogue. So the Bavarian innovator was more criticised as a bungler than credited with a conscious improvement of the art of star-mapping.

A second innovation, however, was given more cordial recep-

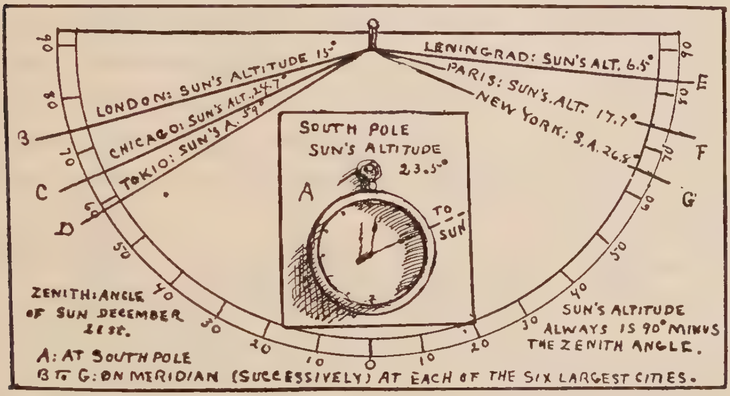


FIG. 111.—The Sun's Altitude December 21 at Seven Locations. Composite picture of Zenith-angle records that might conceivably be made on the same day: (A) at the South Pole, by Admiral Byrd, at any hour of the day; (B) at local noon successively at each of the world's six largest cities.

Note that the sun's altitude at noon is lower at three of the six cities than at the pole. Even at New York and Chicago, the Christmas-Day sun would only for a brief period at mid-day rival the brightness of the sun shining throughout the day at the South Pole. (The altitude is, of course, 90 degrees, *less* the zenith angle.)

tion. At all events, it was accepted ultimately, and remains to this day the standard method of nomenclature. This is the expedient of designating the stars in a constellation, somewhat in the order of their brightness, by the letters of the Greek alphabet. After these are exhausted, the Latin alphabet is introduced. Subsequently, if necessary, the stars are numbered. (Flamsteed's Chart used numbers from the outset.)

It is due to this Bavarian contemporary of Galileo that any one who today wishes to speak about stars must be able to recognise the letters of the Greek alphabet and pronounce their names. Doubtless it did not occur to the innovator that the time might come when there would be highly educated people in the world who would have no other need of that alphabet.

It is obviously convenient, for example, to name Bradley's type star as Gamma Draconis, instead of having describe it as one of the brightish stars in the constellation Dragon. Only of course, it becomes necessary also to remember your Latin genitives. But that also was something that Bayer never dreamed anyone would ever forget.

Names aside, Bayer's chart constituted a map of the heavens, as visible to the naked eye, that all subsequent star-gazers were to find of inestimable value. Of course the locations of stars were only approximate, since accurate location became possible only after eyes had been sharpened by the telescope. The stars even of the keen-eyed Tycho averaged wrong by two minutes of arc.

Keen eyed. But for the matter of that, even the much improved celestial maps made with the use of the telescope, including those of Hevelius and Flamsteed, were rendered suspect—or rather shown to be positively unreliable—by the work of Bradley. If aberration shifts a star by twenty seconds of arc from its true position when the earth is moving in one direction, and shifts it back and as far the other way when the earth is at the opposite side of its orbit—with intermediate shifts between—it is obvious that any given observations to record the position of that star must be dated, else it is valueless, for really accurate comparison.

If dated, the observation may be corrected for aberration, as

well as for nutation. But even this may not be sufficient, unless a record was kept also of the barometric and hydrometric conditions of the atmosphere, which would modify the refraction of light, which makes still another shift in the star's apparent position.

Then, of course, to complete the outline of the story, there are the varied movements of the earth to be taken under consideration—the fact that an observer on the earth's surface does

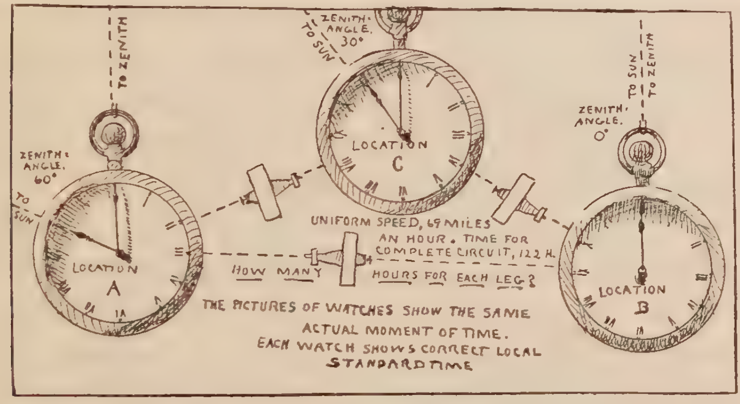


FIG. 112.—The Principle of Eratosthenes Illustrated. See question on the drawing. Answer: 60 hours for leg A-B; 30 hours for leg B-C; 32 hours (122-90) for leg C-A. (This puzzle is exceedingly simple if you know the Eratosthenes principle; but otherwise exceedingly difficult, if not impossible of solution.)

not travel round and round, but forward in a sort of cork-screw spiral.

All in all, the complications are so numerous that observational becomes a mathematical science. Flamsteed and Halley—not to mention Newton—were notable mathematicians. Bradley, however, though by no means without mathematical training, was a better observer than calculator. And when he came to full presentation of the intricacies of nutation, he sought the cooperation

of the French mathematical astronomer, D'Alembert for the completion of the tables.

As illustrating the way in which astronomical data interlock, so to speak, it is worth noting that what is called the "constant" of the aberration of light, as determined by Bradley, may be utilized, if the speed of the earth's orbital motion is known, to calculate the speed of transmission of light itself. Or, contrariwise, the speed of light being known, the orbital speed of the earth may be calculated from the aberration constant.

And since the orbital speed of the earth depends on the earth's distance from the sun, it follows that this distance—which is used as the yard-stick for all planetary measurements—may be determined by the aberration formula.

That is to say, by pointing a telescope at a star, and noting the amount of its shift from a previously determined location, the distance of the earth from the sun may be computed. Not only so, but by many competent mathematicians, including America's greatest, Simon Newcomb, the aberration-of-light method is regarded as the best of all methods for determining this important distance.

Modern charts. The value of the photographic plate for making star-charts was discovered almost by accident. Sir David Gill at the Cape of Good Hope Observatory was taking a photograph of a comet (1864), and in so doing discovered that the stars were registered on the plate. Soon astronomers everywhere were photographing the starry vault, and presently a project was in hand for the photographing of the entire heavens by an association of astronomers in different parts of the world. It has been expected that this colossal task would be completed about the year 1933.

Whether the results will ever be published in full, is somewhat doubtful, owing to the great expense involved.

Of course the average amateur is interested chiefly in the naked-eye stars—those from the first to the sixth magnitude.

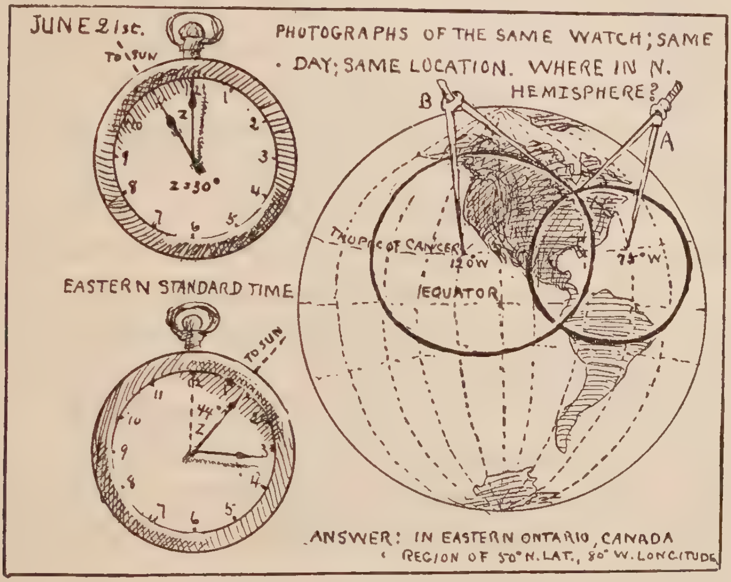


FIG. 113.—LOCATION DETERMINED BY TWO ZENITH-ANGLE TESTS.
Explanation: Zenith angles of 30 and 44 degrees, with sun located on Tropic of Cancer near meridians 75 and 120 respectively. Circles of 30 and 44 degrees radius from these centers intersect in eastern Ontario at about the point named. Only at this location, then, could the two pictures have been taken, as shown, on that day, on the continent of North America. (The second intersection of the circles falls just below the Equator. There is no third place on the globe where the watch could be—unless, of course, it were set for other than Eastern Standard Time.)

Even the additional stars visible through an opera glass do not compete with the ones that are bright enough to show to the naked-eye as first, second, or third magnitude stars.

If one knows these principal large-magnitude stars, one can

of course outline the constellations in a general way, because the constellations were devised to contain these stars—for the obvious reasons that the ancient astronomers had no telescopes.

The charts here presented show all the constellations visible from middle latitudes of the northern hemisphere at one sweep. To avoid confusion, only the brighter stars are shown. After one has learned to recognise a few of the brightest, it is comparatively easy to go on to those of lower magnitudes. Three groups of stars known to everyone are the Big Dipper, the Pleiades, and the Belt of Orion. If one recalls that the two "pointer" stars (known to everyone as pointing to the pole star) lie almost on the 11-hour meridian, this will serve as a sort of point of departure from which to reckon. The northernmost star of the Belt of Orion lies on the celestial equator, at about five and a half hours right ascension. The two stars making the rim of the Big Dipper are about ten degrees apart, and the pointer nearest to the pole star is about 28 degrees from the pole. Other "yard-sticks" will suggest themselves as you become familiar with the stars.

If you study the charts somewhat attentively, noting constantly the right ascension and declination of each important star, and in general terms the bounds of the more important constellations, your progress will be much more rapid than if you merely view the stars at random, without reference to their specific locations.

Since, owing to the earth's orbital movement, each constellation necessarily shifts round the entire circuit of the heavens in a year, the monthly shift is one-twelfth of 360 degrees, or 30 degrees. A constellation that is directly overhead, or on the meridian at nine P.M., July 31st., will be 30 degrees west of

the meridian at the same hour of August 31st. Once you have located the constellations for any month, you will always know where to look for them by bearing in mind the meridional position.

Of course the constellations necessarily swing westward around the circle of the heavens in 24 hours, owing to the earth's rotation. And it is obvious that the shift for two hours on any given night will equal the monthly shift due to the orbital motion. That is to say, if you find a constellation directly on the meridian at nine P.M., you will find it 30 degrees west of the meridian at eleven P.M., of the same night. When you have learned to gauge angular distances, you will know where to look for the stars in accordance with these shifts, and you will be in position of one who in looking up to the heavens feels among old friends.

No other single consideration will enable you to obtain this degree of proficiency with anything like the facility that will result if from the outset you pay attention to the right ascension and declination—in effect the longitude and latitude—of the stars whose acquaintance you wish to cultivate.

A word about the use of the charts. The first-magnitude stars are guide marks that should always be looked for in locating the constellations. If in doubt, squint through nearly closed lids, and the lesser stars will disappear, the big ones standing out. At twilight of dusk or dawn the first-magnitude stars are visible when the sky is otherwise blank. At night a flashlight enables you to use the charts to advantage in the open.

Ordinarily face south, and hold the book upright, or even above the head, until a few prominent guide stars are located. In looking at the circumpolar view, it will be convenient to face north,

and hold the book upside down. The Big Dipper will give the clue to the positions of the northern constellations.

Scale of Magnitudes

It will be seen that on the dark backgrounds of the star charts, the white images of stars are of varying sizes, somewhat in accord with the varying magnitudes of the stars themselves.

About one hundred of the brightest stars are also marked with radiating points, or *rays*, that vary in number. I have endeavored thus, with the aid of the burin, to give a pretty accurate notion of the gradation of magnitudes—in particular among the two-score *Second-Magnitude* stars, which are very important guide marks.

All stars of technical magnitudes 1.50 to 2.50 are said to be of "second magnitude." But the range of brightness between Castor (1.58) and Mintaka (2.48) is very notable. It seemed worth while to sub-divide the group on the charts. The system of *rays* makes this feasible. The plan adopted is this:

Four-ray stars are between magnitudes 1.50 and 2.00; *three-ray* stars between 2.00 and 2.25; and *two-ray* stars between 2.25 and 2.50. This completes the roster of *Second-Magnitude* stars, of which about forty sentinel the northern sky. A few fall on light backgrounds in the circumpolar charts, and are lettered but not rayed. The others will be recognized and appraised at a glance.

The *First-Magnitude* stars, aggressively large and with multiple rays, are of course even more conspicuous.

There remains a scattered group of smaller stars breveted with *one ray*. These are the forty-odd leaders among stars of *Third Magnitude* —those between magnitudes 2.50 and 3.00. The remaining third-magnitude stars (3.00 to 3.50) and the fourth-magnitude stars (3.50 to 4.50) are shown as rayless dots of variant sizes.

As a further aid to identification, the stars of magnitude brighter than 2.75 (with a few omissions) are tabulated below in the sequence in which they cross the meridian. You may locate them on the charts

by following the hour-circles sequentially from right to left (west to east); beginning at 0 meridian, or hour, which is also hour XXIV, at the right side of charts 7 and 8, page 601.

It will be seen that Declinations (latitudes) are also given, so that the precise location of each star on the appropriate chart is as simple as the location by longitude and latitude of, say, your home city on a terrestrial map.

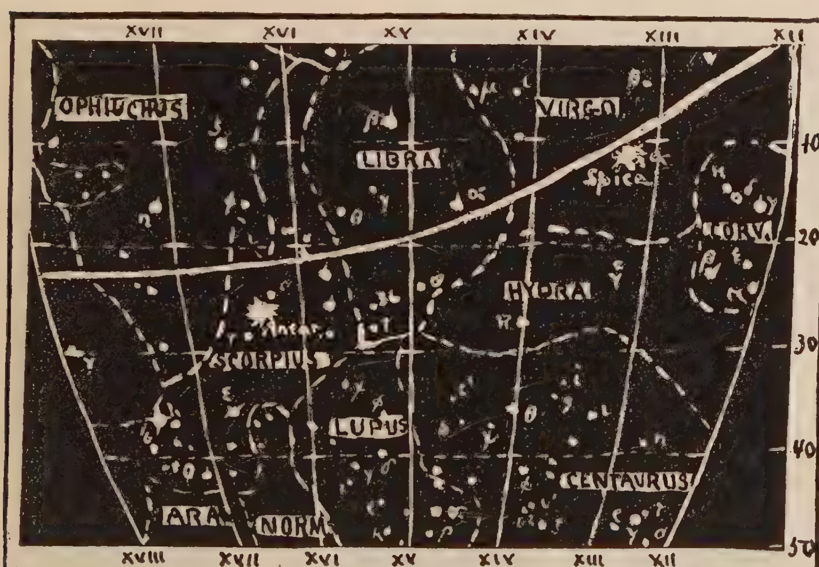
The right ascensions and declinations show "mean positions" for 1930, as given in *The American Ephemeris and Nautical Almanac*—seconds being omitted.

A sweep of the charts under guidance of this tabular census of *rayed* stars will prepare you for rapid progress in the identification of the stars themselves.

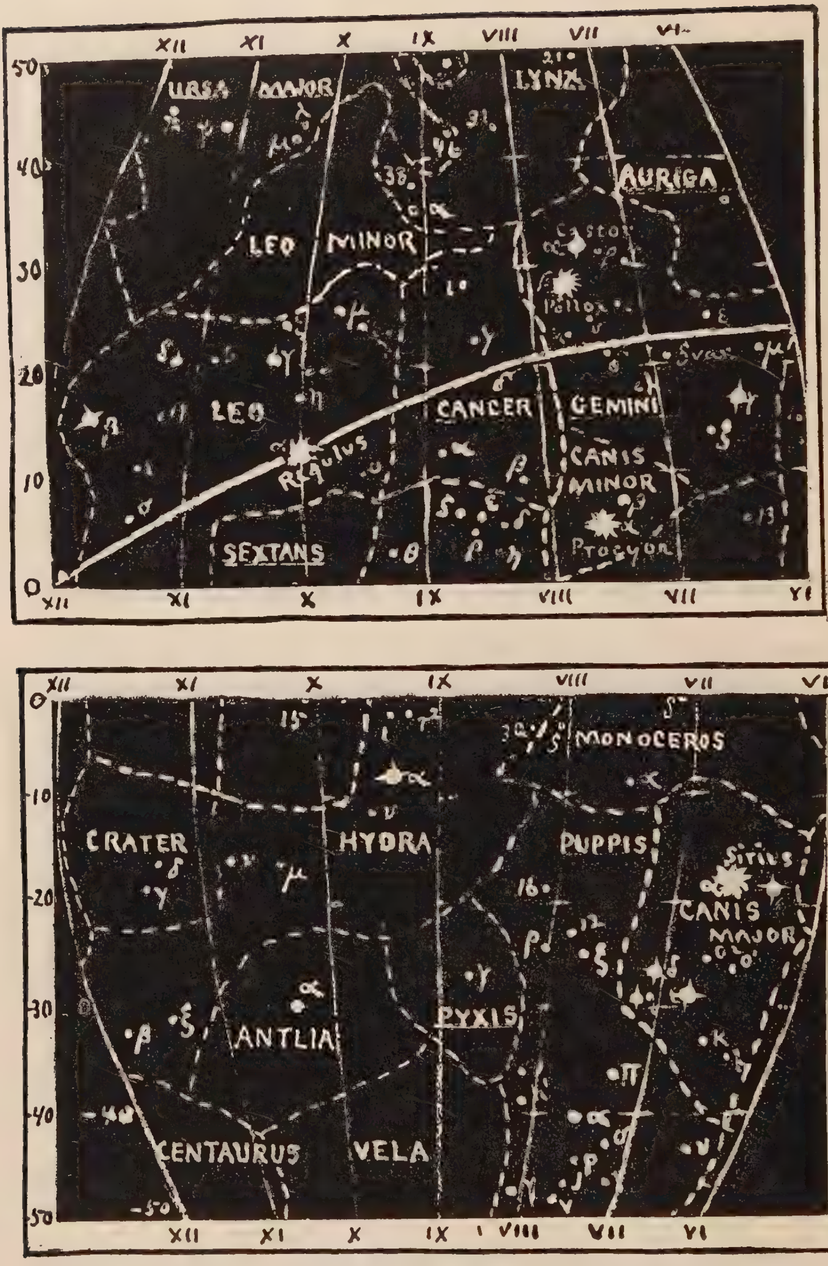
THE BRIGHTEST STARS IN THE ORDER OF RIGHT ASCENSION

No.	Name of Star	Magnitude	Right Ascension H	Right Ascension M	Declination	Chart No.
1	Alpha Andromedae (Alpheratz) ..	2.15	0	4	+28° 42′	7
2	Beta Cassiopeiae (Caph)........	2.42	0	5	+58 45	10
3	Beta Ceti (Deneb Kaitos).......	2.24	0	40	−18 22	8
4	Gamma Cassiopeiae............	2.25	0	52	+60 20	10
5	Beta Andromedae (Mirach)......	2.37	1	5	+35 14	7
6	Gamma Andromedae (Almach)...	2.28	1	59	+41 59	7
7	Alpha Arietis (Hamel)..........	2.23	2	3	+23 7	7
8	Beta Persei (Algol).... Var. 2.30 to	3.50	3	3	+40 41	10
9	Alpha Persei (Mirfak)...........	1.90	3	19	+49 36	7, 10
10	*Alpha Tauri (Aldebaran)*........	1.06	4	31	+16 22	7
11	*Beta Orionis (Rigel)*.............	0.34	5	11	− 8 16	7
12	*Alpha Aurigae (Capella)*.........	0.21	5	11	+45 55	7, 10
13	Beta Tauri (Nath)..............	1.78	5	21	+28 32	7
14	Delta Orionis (Mintaka).........	2.48	5	28	− 0 20	8
15	Epsilon Orionis (Alnilam)........	1.75	5	32	− 1 14	8
16	Gamma Orionis (Bellatrix).......	1.70	5	21	+ 6 17	7
17	Zeta Orionis (Alnitak)...........	2.05	5	37	− 1 58	8
18	Kappa Orionis (Saiph)..........	2.20	5	44	− 9 41	8
19	*Alpha Orionis (Betelgeuse)* Var. 0.5 to	1.10	5	51	+ 7 23	7
20	Beta Aurigae (Menkalinan)......	2.07	5	54	+44 56	7
21	Beta Canis Majoris (Mirzam)....	1.99	6	19	−17 55	6
22	Gamma Geminorum (Alhena)....	1.93	6	33	+16 27	5
23	*Alpha Canis Majoris (Sirius)*.....	−1.58	6	42	−16 37	6

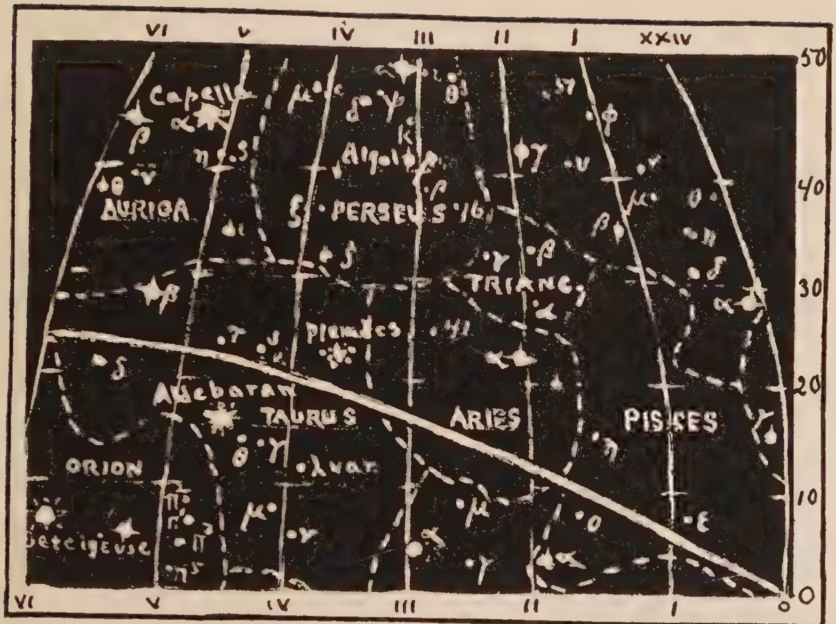
CHARTS 1 AND 2.—The Evening Sky in Autumn. Hour circle XXI crosses local meridian at 9 P.M. September 21, and four minutes earlier each succeeding night.

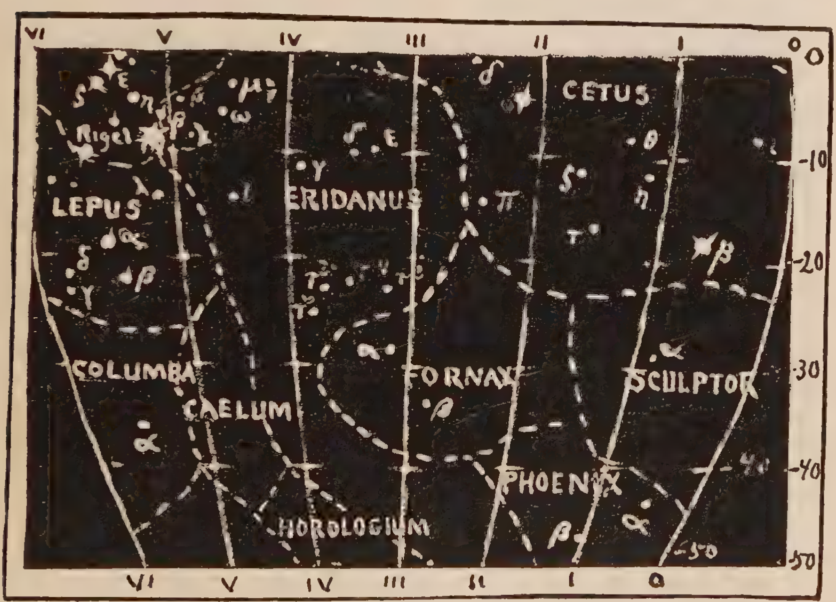


CHARTS 3 AND 4.—The Evening Sky in Summer. Hour circle XV crosses the local meridian at 9 P.M. June 21; an hour earlier July 6; at 7 o'clock July 21; at 5 in the morning February 21.



Charts 5 and 6.—The Evening Sky in Spring. Hour meridian IX is directly overhead at 9 P.M. March 21; at 5 A.M. November 21.





CHARTS 7 AND 8.—The Evening Sky in Winter. Hour circle III crosses the local meridian at 9 P.M. December 21; at 8 P.M. January 6; at 7 P.M. January 21.

TABLE OF THE BRIGHTEST STARS (*Continued*)

No.	Name of Star	Magnitude	Right Ascension		Declination		Chart No.
24	Epsilon Canis Majoris (Adhara)	1.63	6	55	−28	52	6
25	Delta Canis Majoris (Wezen)	1.98	7	5	−26	16	6
26	Eta Canis Majoris (Aludra)	2.43	7	21	−29	9	6
27	Alpha Geminorum (Castor)	1.58	7	30	+32	2	5
28	*Alpha Canis Minoris* (*Procyon*)	0.48	7	35	+ 5	24	5
29	*Beta Geminorum* (*Pollux*)	1.21	7	41	+28	11	5
30	Alpha Hydrae (Alphard)	2.16	9	24	− 8	21	6
31	*Alpha Leonis* (*Regulus*)	1.34	10	4	+12	18	5
32	Gamma Leonis (Algeiba)	2.61	10	16	+20	11	5
33	Beta Ursae Majoris (Merak)	2.44	10	57	+56	45	9
34	Alpha Ursae Majoris (Dubhe)	1.95	10	59	+62	7	9
35	Delta Leonis (Zosma)	2.58	11	10	+20	54	5
36	Beta Leonis (Denebola)	2.23	11	45	+14	57	5
37	Gamma Ursae Majoris (Phecda)	2.54	11	50	+54	5	9
38	Epsilon Ursae Majoris (Alioth)	1.68	12	50	+56	20	9
39	Zeta Ursae Majoris (Mizar)	2.40	13	21	+55	17	9
40	*Alpha Virginis* (*Spica*)	1.21	13	21	−10	47	4
41	Eta Ursae Majoris (Alkaid)	1.91	13	44	+49	39	9
42	*Alpha Bootis* (*Arcturus*)	0.24	14	12	+19	34	3
43	Epsilon Bootis (Tzar)	2.70	14	41	+27	22	3
44	Beta Librae (Zubeneschamali)	2.74	15	13	− 9	7	4
45	Alpha Coronae Borealis (Alphecca)	2.31	15	31	+26	56	3
46	Delta Scorpii (Dschubba)	2.54	15	56	−22	25	4
47	*Alpha Scorpii* (*Antares*)	1.22	16	25	−26	16	4
48	Zeta Ophiuchi	2.70	16	33	−10	25	4
49	Epsilon Scorpii	2.36	16	45	−34	10	4
50	Eta Ophiuchi (Sabik)	2.63	17	6	−15	38	4
51	Lambda Scorpii (Schaula)	1.71	17	28	−37	3	4
52	Alpha Ophiuchi (Ras Alhague)	2.14	17	31	+12	36	3
53	Gamma Draconis (Etamin)	2.42	17	54	+51	29	9
54	Epsilon Sagittarii (Kaus Australis)	1.95	18	19	−34	25	2
55	*Alpha Lyrae* (*Vega*)	0.14	18	34	+38	43	1
56	Sigma Sagittarii (Nunki)	2.14	18	50	−26	23	2
57	*Alpha Aquilae* (*Altair*)	0.89	19	47	+ 8	40	1
58	Gamma Cygni (Sadr)	2.32	20	19	+40	1	1
59	*Alpha Cygni* (*Deneb*)	1.33	20	39	+45	1	1
60	Epsilon Pegasi (Enif)	2.54	21	40	+ 9	53	1
61	*Alpha Piscis Austrini* (*Formalhaut*)	1.29	22	53	−29	59	2
62	Beta Pegasi (Scheat)	2.61	23	0	+27	42	1
63	Alpha Pegasi (Mirfak)	2.57	23	1	+14	49	1

Chart 9: Circumpolar Region, Hours VI to XVIII

Chart 10: Circumpolar Region, Hours XVIII to VI

Map A: The Summer Constellations, Hours XII to XXIV

Map B: THE WINTER CONSTELLATIONS, HOURS O (XXIV) TO XII

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A NOTE ABOUT THE AUTHOR

Dr. Henry Smith Williams, B.Sc., M.D., LL.D., occupies a unique place in the scientific and literary world. His professional reputation as a physician was gained largely by work with the microscope and the writing of technical articles on the brain and mind. At 28 he was selected for the position of Medical Superintendent of a large metropolitan hospital. Subsequently he practised as a neurologist and psychiatrist in New York for several years; then went abroad for a sojourn in Europe which, with two interruptions, extended over a period of about ten years—devoted to intensive research in hospitals, museums, universities and libraries, with incidental study of art in Paris, Munich and Italy.

The results of these studies appeared in the form of three vast works: *The Historians' History of the World, The Art of Writing* and *A History of Science,* aggregating 40 volumes, and in various minor works; and in numerous articles in magazines, contributions to the Encyclopædia Britannica, and other learned works. Amid all these varied interests, Dr. Williams has found ample leisure to pursue consistently a boyhood enthusiasm for Astronomy which began when, as an eight-year-old, he noticed the discrepancy between the two accounts of creation in Genesis. He has contributed many magazine articles on new astronomical developments and has given much attention to the practical observational work which links Astronomy so closely with Navigation. Among his original scientific contributions to this field is his extension of Professor Wesener's Floating-continent hypothesis dealing with the origin of the great land-masses.